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BULLETIN
OF THE
SEISMOLOGICAL SOCIETY
OF AMERICA

VOLUME XI
1921

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Bulletin of the Seismological Society of America

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MARCH, 1921

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Ruined Arches of the San Juan Capistrano Mission

The San Juan Capistrano Mission is situated midway between Los Angeles and San Diego. As described in the accompanying article by Dr. Carpenter, this mission was so badly damaged by the great earthquake of 1812 that it was never rebuilt. It was one of the most beautiful of all of the examples of Moorish architecture found in the California missions. These arches, which have stood for over one hundred years, are proof that no serious earthquake has occurred in that locality since.

The Bulletin of the Seismological Society of America

VOL. XI.

MARCH, 1921

No. 1.

EARLY RECORDS OF EARTHQUAKES IN SOUTHERN CALIFORNIA¹

By FORD A. CARPENTER

The recent earthquake shocks in Inglewood and in the vicinity of Los Angeles, Cal., have focused attention upon this locality as one subject to seismic disturbances. In order to determine some of the results of earthquakes prior to the settlement of this region by the whites, early Mission Fathers' documents have been searched and the following pages contain practically all references to earthquakes during the last of the eighteenth century and the first of the nineteenth century.

One of the most significant facts brought out in a study of the old records is that the Santa Ana River was originally named the "Rio Jesus de los Temblores." By referring to Dr. Stephen Taber's article on the Inglewood earthquake, in the BULLETIN of September, 1920, it will be seen from the accompanying plate to his article showing the isoseismals (page 134), that the San Onofre fault line bisects the Rio Jesus de los Temblores, or what is now the Santa Ana River.

The following list of earthquakes and descriptive extracts are taken from a book by the Rev. Father Englehardt.²

LIST OF EARTHQUAKES

<i>Date</i>	<i>Place</i>
July 24, 1769	Near Los Angeles (site of Mission San Gabriel).
October 11-31, 1800	San Juan Bautista.
December 8, 1812	San Juan Capistrano.
December 8, 1812	San Gabriel.
December 21, 1812	La Purissima Concepcion.
December 21, 1812	San Fernando.
December 21, 1812	Santa Inez.
December, 1812	San Buenaventura.
December, 1812	Santa Barbara.

On the 24th (July 24, 1769) they camped in sight of the islands of San Clemente and Santa Catalina, and reported San Pedro Bay as being five leagues distant. The 28th of July found the party encamped near a river, which they

¹ Compiled from the records of the Mission Fathers by the Department of Meteorology and Aeronautics of the Los Angeles Chamber of Commerce.

² "The Franciscans in California." Fr. Zephyrin Englehardt. O. S. F. (Printed and published at the Holy Childhood Indian School, Harbor Springs, Mich., 1897.)

called "Temblores," because all that day and night they felt terrific shocks of earthquake. This was the Santa Ana River, or Rio Jesus de los Temblores.³

There were shocks of earthquake from the 11th to the 31st of October, 1800, sometimes six in a day, the most severe being on the 18th. The Fathers were so terrified that they spent the nights out of doors. Several cracks appeared in the ground, and of considerable extent and depth on the banks of the Pajaro, and the adobe walls of all the buildings were cracked from top to bottom, and threatened to fall.⁴

A series of earthquake shocks, the most disastrous, if not the most severe, that ever occurred in California, caused the wildest terror throughout the southern part of the province in 1812. The year was ever after known as "el año de los temblores," and was for San Juan Capistrano particularly unfortunate. It occurred during early mass on Sunday, December 8th, when about fifty persons were in the church. The edifice was of the usual cruciform shape, with very thick walls and arched domelike roof, all constructed of stone imbedded in mortar or cement. The stones were not hewn, but of irregular size and shape. The lofty tower at the church front fell with a crash on the vaulted roof at the second shock, and in a moment the immense mass of stone and mortar came down upon the little congregation. The celebrant, just then at the offertory of the Mass, escaped by the door of the sacristy, and six neophytes besides were saved as by a miracle; but the rest, forty in number according to the official reports, were crushed to death. In the search for bodies much of the debris was removed from the interior; but otherwise the ruin of the most beautiful mission structure in California still stands as it was left in 1912.⁵

There was constant alarm at San Gabriel on account of the Indians in 1811, and for some years thereafter; but the savages attempted nothing against the mission. It suffered some damage, from another cause, however. An earthquake occurred on December 8, 1812, at sunrise, and overthrew the main altar, breaking the statues of Our Lord, St. Joseph, St. Dominic, and St. Francis. Moreover, the top of the steeple was brought down, and the sacristy, the convent of the missionaries, and other buildings were damaged.⁶

On December 21, 1812, there was an earthquake while the Fathers were making their examination of conscience. The earth shook so violently that it was difficult to stand. A brief examination showed that the church walls had been thrown out of plumb. Just before 11 o'clock there came another more violent shock which brought down the church and nearly all the mission buildings, besides about one hundred neophyte houses of adobe. The earth opened in several places and emitted water and black sand. Several persons were wounded, but none was killed. Subsequent floods completed the devastation, so that very few buildings were worth repairing.⁷

The earthquake of December 21, 1812, did no further damage than to necessitate the introduction of thirty new beams to support the church wall.⁸

³ *Ibid.*, part I, chapter 5, p. 44.

⁴ *Ibid.*, part II, chapter 20, p. 399, San Juan Bautista.

⁵ *Ibid.*, part II, chapter 11, pp. 319-321, San Juan Capistrano.

⁶ *Ibid.*, part II, chapter 6, pp. 272-273, San Gabriel.

⁷ *Ibid.*, part II, chapter 16, p. 365, La Purissima Concepcion.

⁸ *Ibid.*, part II, chapter 22, p. 414, San Fernando.

The earthquake of December 21, 1812, two shocks fifteen minutes apart, brought down a corner of the church at Santa Inez, destroying one fourth of the new houses near the church, ruined all the mission roofs, and cracked many walls; but the Fathers did not deem the damage irreparable.⁹

In December, 1812, three heavy shocks of earthquake occurred at San Buenaventura, which damaged the church to such an extent that the tower and much of the façade had to be rebuilt. The whole mission site appeared to settle, and the fear of being engulfed by the sea drove all away to San Joaquin y Santa Ana, where they remained until April, 1813.¹⁰

During the month of December, 1812, several earthquake shocks were felt. These shocks were so severe that all the mission buildings were badly damaged; the church in particular had suffered so much that it was thought more expedient to take it down and erect a new one than to make repairs. A new stone church was accordingly commenced in 1815, but not completed until September, 1820.¹¹

⁹ *Ibid.*, part II, chapter 24, p. 434, Santa Inez.

¹⁰ *Ibid.*, part II, chapter 13, p. 341, San Buenaventura.

¹¹ *Ibid.*, part II, chapter 14, p. 354, Santa Barbara.

THE SOUTHWEST SECTION OF THE SEISMOLOGICAL SOCIETY OF AMERICA

By FRANK ROLFE

The Inglewood Earthquake of June 21, 1920, followed by the earthquake of July 16, 1920, with its center apparently close to the business center of Los Angeles City, naturally awakened considerable interest in the study of earthquakes in Southern California.

Unfortunately the services of two men, who hitherto had rendered the most assistance to the Seismological Society of America in studying earthquakes in Southern California, were not available at this time, Mr. Homer Hamlin having died, and Dr. Ralph Arnold being absent in the East on business.

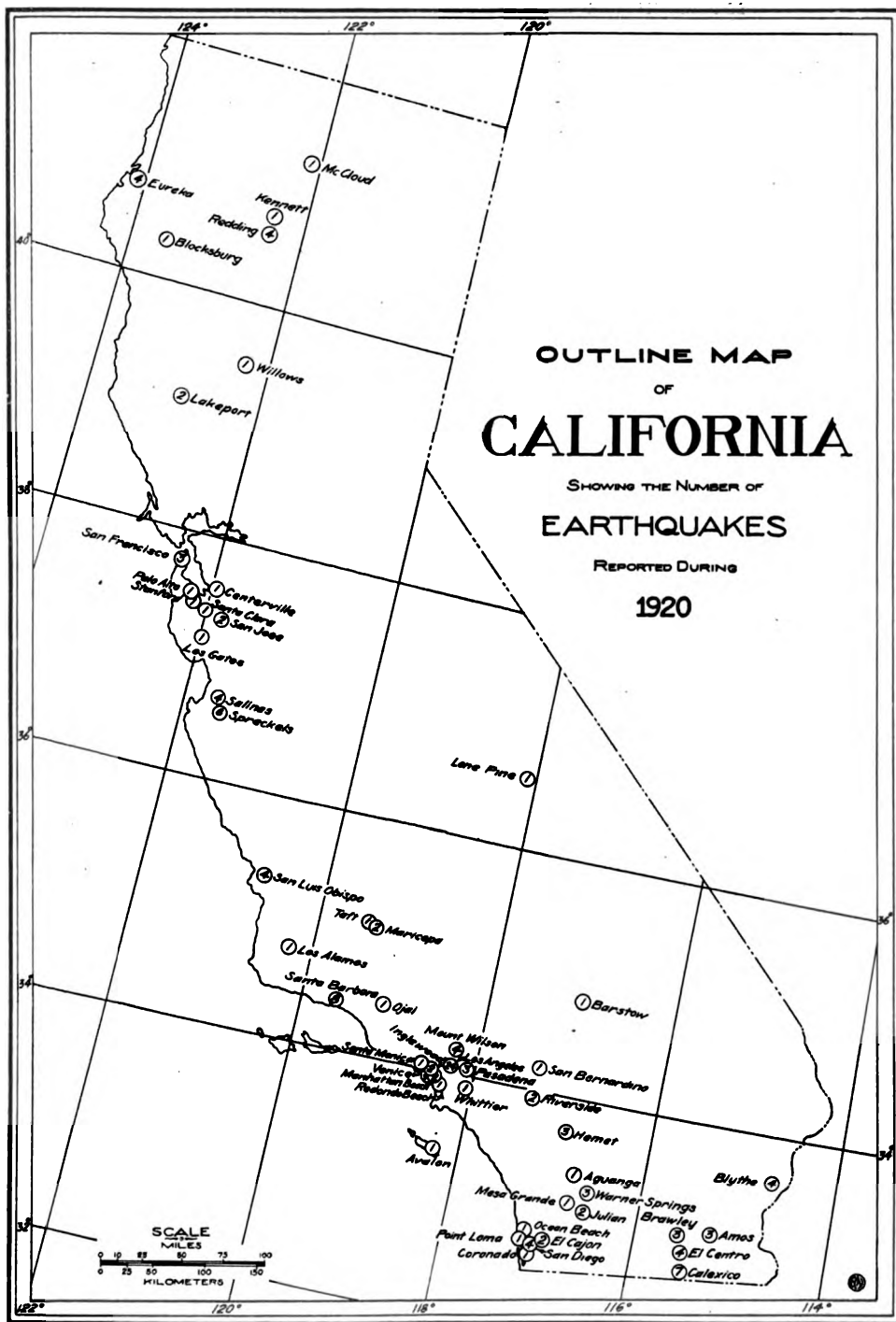
However, the investigation of these important shocks was begun at once, Dr. Branner very promptly sending down Dr. Stephen Taber, one of the foremost of American seismologists, who was at that time lecturing on seismology at the summer quarter of Stanford University. Working independently of Dr. Taber, Mr. Homer Laughlin, Jr., one of the early members of the Seismological Society of America, and who for a number of years has been making a study of the location of the lines of action of earthquakes in Southern California, spent a great deal of time in studying the effects of these shocks.

Soon after Dr. Arnold returned to Los Angeles, in August, 1920, a meeting of the Southern California Chapter of the American Institute of Mining and Metallurgical Engineers was called, the subject of earthquakes being given special consideration, Dr. Stephen Taber, Mr. William Mulholland, Dr. Robert T. Hill, and Dr. Ralph Arnold taking leading parts in the discussion. At the conclusion of the meeting, Dr. Arnold appointed an executive committee of ten, with Mr. Mulholland as chairman, to take up the matter of organizing a local section of the Seismological Society of America. This committee has held three meetings in Mr. Mulholland's office. It was decided to canvass the members of the local technical societies, and to send out with the letters a copy of the BULLETIN OF THE SEISMOLOGICAL SOCIETY OF AMERICA giving an account of the recent earthquakes in the vicinity of Los Angeles, the committee becoming financially responsible for the expense incurred in securing the bulletins. This canvass was carried on by Mr. Homer

Laughlin, Jr., the secretary of the committee, and it was due very largely to his efforts that forty-five new members were secured for the Seismological Society of America. Dr. Arnold and Dr. Ford A. Carpenter also have been the means of securing a number of new names, and have shown a great deal of interest in the work of the society. Although a very busy man, Mr. William Mulholland, chief engineer of the Los Angeles Aqueduct, consented to act as chairman of the committee and render what assistance he could.

The first regular meeting of the Southwest Section of the Seismological Society of America was held in Los Angeles at the home of Mr. Homer Laughlin, Jr., on the evening of January 25, 1921. Mr. William Mulholland was elected President, Dr. Ralph Arnold and Mr. Frank Rolfe Vice-Presidents, and Mr. Homer Laughlin, Jr., Secretary and Treasurer. Plans were discussed for the carrying on of the work of earthquake investigation and special committees appointed to direct this work. Mr. Homer Laughlin, Jr., read a comprehensive paper giving the result of special studies made by him on the Inglewood earthquake of June 21, 1920.

The purpose of the Southwest Section of the Seismological Society is to assist in every way possible the parent society in its work in the study of earthquakes. As yet it is hardly organized, but it hopes in the near future to be of real assistance to Dr. Branner and other members who have worked so faithfully to promote the study of this great subject.



CALIFORNIA EARTHQUAKES DURING 1920

By ANDREW H. PALMER, *Meteorologist, U. S. Weather Bureau.*

Detailed records are now kept of all sensible earthquakes which occur in California. While those earthquakes which occur in the uninhabited desert and mountain regions pass unrecorded, those which occur in the inhabited portions of the State are eventually reported, and it is believed that few of the latter escape record. The principal sources of information are the following:

(1) The United States Weather Bureau maintains a special seismological service for which data are furnished by approximately 350 correspondents well distributed throughout California. These correspondents are each supplied with cards on which they are instructed to enter specified data concerning each earthquake observed. These data include date, time, intensity, duration, number of shocks, direction of movement, sounds, miscellaneous phenomena, etc., together with the reporter's name and address. The cards are assembled in the San Francisco office of the Weather Bureau, and are subsequently forwarded to the Central Office in Washington, where the data are published in the *Monthly Weather Review*, an official government publication.

(2) The Seismological Society of America frequently publishes in this BULLETIN reports of earthquakes forwarded to its Secretary by members and other correspondents resident in this State.

(3) The daily press frequently publishes news items of earthquakes, though this service usually includes only the larger cities and towns, and dispatches are not often forwarded unless the shocks are severe, or damage has resulted.

A total of 87 separate and distinct earthquakes were felt in California during 1920, based upon data secured from the various sources indicated above. The monthly distribution of occurrence was as follows:

Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Year.
3	2	6	2	5	13	20	2	7	6	1	20	87

Earthquakes were felt during the year in 51 different cities and towns. Places which experienced three or more during the year, and the number felt in each case, were as follows:

Blythe, 4; Brawley, 3; Calexico, 7; El Centro, 4; Eureka, 4; Hemet, 3; Los Angeles, 24; Mount Wilson, 4; Pasadena, 3; Redding, 4; Salinas, 4; San Diego, 4; San Francisco, 3; San Luis Obispo, 4;

Santa Barbara, 8; Spreckels, 6; and Warner Springs, 3.

No earthquakes were felt during 1920 at Berkeley, Fresno, Oakland, Red Bluff, Sacramento, Santa Rosa, or Stockton. But one occurred in the Sacramento Valley, at Willows. The only earthquakes felt in the San Joaquin Valley were two light shocks which occurred in the Kern County oil fields. None was reported from the Sierra Nevada Mountains or from the northeastern plateau region. But one feeble shock was felt in the Owens Valley, at Lone Pine, a recognized epicenter. One occurred on Santa Catalina Island, at Avalon. None was felt on San Miguel Island.

The approximate locations of most of the places at which earthquakes were felt during 1920, and the number felt at each place are indicated on the accompanying outline map of California. From this map it is readily apparent that earthquakes during 1920 were more frequent along the coast than in the interior, and, moreover, they were more numerous in southern than in northern California.

But 19 of the 87 earthquakes which occurred during 1920 were sufficiently widespread to be felt at two or more adjacent stations. The other 68 were so feeble and local that they were felt at one station only. Classified as to intensity, the 137 reports received during the year were as follows, in the adapted Rossi-Forel scale used by the Weather Bureau:

II, 15; III, 59; IV, 32; V, 19; VI, 7; VII, 2; and VIII, 3.

Classified as to the number of shocks or vibrations attending these earthquakes, the data collected were as follows:

One shock, 115 reports; 2 shocks, 15 reports; 3 shocks, 4 reports; 4 shocks, 1 report; and 5 shocks, 1 report.

In regard to the duration of vibrations, the reports received during 1920 presented the following evidence:

One second or less, 5 reports; 2 seconds, 25 reports; 3 seconds, 12 reports; 4 seconds, 4 reports; 5 seconds, 12 reports; and over 5 seconds, 27 reports.

Of the 137 reports received, 108, or 79 per cent, made no mention of sounds having been heard before, with or after the shocks. In the 29 cases in which sounds were heard, they were described as follows:

Rumbling, 14 reports; faint, 10 reports; rattling, 4 reports; and loud, 1 report.

NOTES ON INDIVIDUAL EARTHQUAKES

January 30, 1920.—Santa Barbara was the center of unusual seismicity on the afternoon of January 30th. Between 3:30 p. m. and

5:07 p. m. seven distinct earthquakes were felt, each consisting of but one shock. All were light in intensity, varying from II to III in the Rossi-Forrel scale. They were distinctly felt along the waterfront of the city, but not on the hills on which a portion of the residence section of the city is built. No earthquakes were felt that day by the correspondent residing on San Miguel Island, which is across the Santa Barbara Channel from the mainland.

June 21, 1920.—For a report of this remarkable earthquake see this BULLETIN, 10, 129, September, 1920. This earthquake occurred at 6:47 p. m., and was the strongest and most destructive shock of the year in California. Its maximum intensity was between VIII and IX in the Rossi-Forrel scale. It was felt over an area of about 11,000 square miles, or 29,000 square kilometers. It was felt throughout the coastal plain immediately south of the Santa Monica Mountains. The destructive effects were greatest at Inglewood, about ten miles southwest of the business portion of Los Angeles. The disturbance was due to a small vertical displacement of the rocks on the Inglewood-Newport-San Onofre fault. Damage in excess of \$100,000 resulted. A few persons were injured by falling debris, but no one was killed. The earthquake occurred at a time when most people were at dinner. Moreover, as the day was hot, few people were on the streets. For these reasons there was no loss of life. Had the sidewalks been crowded with pedestrians when the front walls of buildings fell outward, there would doubtless have been many casualties. Many people were badly frightened, and some spent the following night out of doors. One woman died of heart failure when she attempted to run during the earthquake.

July 16, 1920.—For a report of this earthquake see this number of the BULLETIN, page 63. Four distinct shocks were felt in Los Angeles, in addition to minor preliminary and subsequent tremors. Severe shocks having an estimated intensity of about VI occurred at 10:08 a. m., 1:27 p. m., and 1:30 p. m. A final shock of intensity III occurred about 6:14 p. m. These earthquakes caused general alarm, and they were widely heralded by the daily press. Many amusing stories are told of the anxiety with which persons fled from buildings following each of these shocks. Numerous residents spent the following night out of doors. Not a few transients left the city earlier than they had anticipated.

July 22-23, 1920.—Redding was the center of marked seismicity on July 22d-23d. Four violent shocks occurred. The strongest of

the four was the first, which occurred about 8 p. m. on the 22d. The intensity of this vibration was estimated at VIII. Windows were broken and chimneys were demolished. General consternation followed, and many residents slept out of doors during the night, fearing a recurrence of the disturbance. The three other shocks followed within sixteen hours, but none was as violent as the first. They were the only earthquakes experienced in that vicinity in the course of the year. As Redding is not normally a region of high seismicity these disturbances were all the more remarkable.

December 19, 1920.—For four days, December 18th–21st, inclusive, seismic disturbances were frequent in the Imperial Valley and in the desert plateau to the northeast. Because of the sparsely settled character of the region the data secured are meager. However, Mr. M. D. Witter, editor of the *Brawley News*, kindly furnished the following information in connection with the shock felt in Brawley on the evening of December 19th:

This earthquake was followed by one of considerable intensity at 7:45 on the morning of December 20th, intensity VII, on adapted Rossi-Forel scale. Occasional light shocks continued through the day of December 20th, and a second heavy temblor occurred on the morning of December 21st, with almost the same intensity as the one on the morning of December 20th. Shocks were not felt severely at El Centro or Calexico, but were heavy at Westmoreland. Mud geysers at Salton Sea had been active for several days previous to the shocks.

GENERAL CONSIDERATIONS

From a seismological viewpoint, the feature of the year 1920 in California was the large number of earthquakes in Los Angeles and vicinity, the greatest of which occurred on June 21st at Inglewood. No earthquakes were reported from Los Angeles during the first five months of the year. But seven occurred there in June, twelve in July, one in August, and four in September, making a total of twenty-four for the year. The city received much unwelcome publicity in eastern newspapers in connection with these disturbances. The great shock of June 21st was heralded by the eastern press with front-page headlines quite as large as those which announced the San Francisco disaster of 1906. It was unfortunate that first reports published in eastern newspapers gave the impression that another catastrophe had occurred in California. It was amusing to note the feverish efforts made by Los Angeles business interests to counteract these false reports. (While earthquakes may be of great scientific interest, they do not attract tourists or prospective residents.)

Lassen Peak displayed sporadic volcanic activity during 1920 without simultaneous seismic activity in northern California. The recent cycle of activity appears to be nearing a close, without any apparent effect from a seismic viewpoint.

It is worthy of note that not a single month has passed during the past six years without one or more earthquakes in California. One draws the inevitable conclusion that these slight but constantly recurring tremors may well be regarded as a safety valve in efficient operation. However, the earthquake menace is constantly present, and a great shock may be possible at any time.

There were in operation in California during 1920 the following instruments for detecting earthquakes:

Standard seismographs:

Berkeley—University of California.

Mount Hamilton—Lick Observatory.

Santa Clara—University of Santa Clara.

Seismoscopes:

Point Loma—Raja Yoga Academy.

Los Gatos—Mr. Irving H. Snyder.

In view of the marked seismicity in Los Angeles and vicinity during recent years, it is evident that there is urgent need of a standard seismograph in that city. The business interests of Los Angeles should be made to realize that a standard seismograph would be an asset to their community. It is better to publish a truthful scientific presentation of earthquake data than exaggerated and terrifying rumors. News-distributing organizations and daily newspapers would welcome such an innovation. Editors of metropolitan newspapers prefer to publish facts coming from a trustworthy source rather than hearsay evidence picked up by reporters on the street. It is remarkable that though successful business men recognize the value of truth in advertising they have not yet realized the value of scientific facts in matters of this kind.

Table I is a summary of all the California earthquake reports received during 1920. The time of occurrence given in the table is the approximate Pacific, or 120th meridian time, and the hours are numbered 0 to 23, inclusive. Great accuracy of time is not assumed, as the time of observation was, in most cases, that taken from a pocket watch, or from an ordinary household clock.

TABLE I.—NON-INSTRUMENTAL EARTHQUAKE REPORTS, CALIFORNIA, 1920.

DATE 1920	Approx. Time 120th Mer.	STATION	Approx. Lat. (N.)	Approx. Long. (W.)	Intensity R-F	Number of Shocks	Duration Seconds	SOUNDS
Jan. 1	H. M. 6:45	Coronado.....	32°40'	117°12'	3	1	.....	None
Jan. 30	15:30	Santa Barbara.....	34°23'	119°40'	3	1	2	None
Jan. 30	15:33	Santa Barbara.....	.....	.....	2	1	2	None
Jan. 30	15:35	Santa Barbara.....	.....	.....	2	1	2	None
Jan. 30	15:38	Santa Barbara.....	.....	.....	2	1	2	None
Jan. 30	17:00	Santa Barbara.....	.....	.....	3	1	2	None
Jan. 30	17:03	Santa Barbara.....	.....	.....	3	1	2	None
Jan. 30	17:07	Santa Barbara.....	.....	.....	3	1	2	None
Feb. 8	18:20	Julian.....	33°05'	116°37'	5	1	5	Rumbling
Feb. 9	3:30	Julian.....	.....	.....	3	1	8	Rumbling
Feb. 9	3:30	Mesa Grande.....	33°12'	116°45'	3	1	13	Faint
Mar. 3	19:25	El Segundo.....	33°56'	118°22'	4	1	.....	Rumbling
Mar. 3	19:25	Manhattan Beach.....	33°52'	118°22'	4	1	.....	Rumbling
Mar. 3	19:25	Redondo Beach.....	33°50'	118°22'	4	1	.....	Rumbling
Mar. 8	21:50	Calexico.....	32°41'	115°30'	3	1	5	None
Mar. 8	22:03	El Centro.....	32°50'	115°32'	4	1	.....	None
Mar. 18	5:40	Hemet.....	33°45'	116°58'	2	1	2	Faint
Mar. 19	23:04	San Luis Obispo.....	35°13'	120°45'	2	1	2	None
Mar. 20	9:30	Blocksburg.....	40°17'	123°39'	4	1	.....	None
Mar. 20	9:30	Eureka.....	40°45'	124°15'	4	1	20	None
Apr. 12	20:35	Calexico.....	32°41'	115°30'	3	2	5	Rumbling
Apr. 19	22:20	Eureka.....	40°45'	124°15'	3	1	2	None
May 6	17:59	San Luis Obispo.....	35°13'	120°45'	4	1	5	None
May 17	22:25	El Centro.....	32°50'	115°35'	5	2	12	None
May 17	22:25	Warner Springs.....	33°15'	116°45'	4	1	30	None
May 17	22:26	Calexico.....	32°41'	115°30'	5	2	25	None
May 17	22:30	El Cajon.....	32°48'	116°58'	4	1	5	None
May 20	5:30	San Diego.....	32°40'	117°10'	5	1	1	None
May 20	6:30	San Diego.....	32°40'	117°10'	4	1	2	None
June 2	21:55	Kennett.....	40°45'	122°23'	3	2	.....	None
June 10	2:53	Lakeport.....	39°03'	122°56'	3	1	5	Rumbling
June 16	4:15	Salinas.....	36°41'	121°40'	3	1	7	None
June 16	4:15	Spreckels.....	36°38'	121°38'	5	2	3	Faint
June 18	2:08	Los Angeles.....	34°03'	118°15'	3	1	3	None
June 18	2:09	Mount Wilson.....	34°13'	118°04'	2	1	2	None
June 18	2:10	Avalon.....	33°15'	118°15'	3	1	.....	None
June 20	23:20	Warner Springs.....	33°15'	116°45'	3	2	.....	None
June 21	12:24	Barstow.....	34°54'	117°02'	3	2	2	Faint
June 21	18:45	Santa Monica.....	34°02'	118°30'	5	1	10	Rattling
June 21	18:47	Inglewood.....	33°57'	118°23'	8	1	30	None
June 21	18:47	Venice.....	33°58'	118°28'	7	5	.....	Rattling
June 21	18:47	Los Angeles.....	34°03'	118°15'	8	1	12	None
June 21	18:48	Mount Wilson.....	34°13'	118°04'	3	1	5	None
June 21	18:50	Pasadena.....	34°05'	118°10'	3	2	6	None
June 22	5:00	Los Angeles.....	34°03'	118°15'	4	1	.....	None
June 22	5:00	Venice.....	33°58'	118°28'	4	1	.....	None
June 22	12:30	Los Angeles.....	34°03'	118°15'	4	1	.....	None
June 22	12:30	Inglewood.....	33°57'	118°23'	5	1	.....	None
June 23	4:00	Los Angeles.....	34°03'	118°15'	3	1	.....	None
June 23	5:00	Los Angeles.....	.....	.....	3	1	.....	None
June 28	1:01	San Luis Obispo.....	35°13'	120°45'	5	1	10	None
June 29	20:08	Los Angeles.....	34°03'	118°15'	3	1	.....	None

TABLE I.—NON-INSTRUMENTAL EARTHQUAKE REPORTS, CALIFORNIA, 1920.—*Cont.*

DATE 1920	Approx. Time 120th Mer.	STATION	Approx. Lat. (N.)	Approx. Long. (W.)	Intensity R-F	Number of Shocks	Duration Seconds	SOUNDS
July 5	H. M. 7:55	Whittier.....	34°00'	118°04'	3	1	.....	None
July 9	21:25	Los Angeles.....	34°03'	118°15'	4	3	2	None
July 16	10:08	Los Angeles.....	.....	.....	6	1	4	None
July 16	13:26	Pasadena.....	34°05'	118°10'	3	1	5	None
July 16	13:27	Los Angeles.....	34°03'	118°15'	6	1	3	None
July 16	13:27	Mount Wilson.....	34°13'	118°04'	2	1	2	None
July 16	13:30	Los Angeles.....	34°03'	118°15'	6	1	3	None
July 16	13:30	Mount Wilson.....	34°13'	118°04'	3	1	2	None
July 16	13:30	Pasadena.....	34°05'	118°10'	6	1	10	None
July 16	18:14	Los Angeles.....	34°03'	118°15'	3	1	1	None
July 22	19:55	McCloud.....	41°15'	122°10'	3	1	.....	None
July 22	20:00	Redding.....	40°35'	122°25'	8	1	.....	None
July 23	6:00	Redding.....	40°35'	122°25'	6	1	.....	None
July 23	8:00	Redding.....	.....	.....	6	1	.....	None
July 23	12:00	Redding.....	.....	.....	6	1	.....	None
July 26	4:12	Los Angeles.....	34°03'	118°15'	3	2	2	Faint
July 26	4:15	Los Angeles.....	.....	.....	4	1	2	Rattling
July 27	0:02	Los Angeles.....	.....	.....	3	1	2	Faint
July 27	13:00	Los Angeles.....	.....	.....	3	1	.....	None
July 27	14:09	Los Angeles.....	.....	.....	3	1	3	Rumbling
July 28	7:40	San Bernardino.....	.....	.....	4	1	.....	None
July 28	7:49	Riverside.....	33°58'	117°26'	4	1	.....	None
July 28	11:28	Los Angeles.....	34°03'	118°15'	4	1	2	None
July 29	19:00	Los Angeles.....	.....	.....	4	1	.....	None
Aug. 17	23:20	Salinas.....	36°41'	121°40'	3	1	5	None
Aug. 23	15:10	Los Angeles.....	34°03'	118°15'	4	3	.....	None
Sept. 2	20:50	Los Angeles.....	.....	.....	2	3	3	None
Sept. 3	5:00	Los Angeles.....	.....	.....	2	1	.....	None
Sept. 9	8:44	Palo Alto.....	37°30'	122°06'	3	2	2	None
Sept. 9	8:47	San Jose.....	37°15'	121°53'	5	1	10	None
Sept. 9	8:47	Santa Clara.....	37°21'	121°56'	5	1	.....	None
Sept. 9	8:47	Stanford Univ.....	37°26'	122°12'	3	1	3	None
Sept. 9	8:50	Centerville.....	37°30'	122°00'	2	1	10	Rumbling
Sept. 9	8:57	San Francisco.....	37°48'	122°26'	2	1	3	None
Sept. 10	6:15	Riverside.....	33°58'	117°26'	4	1	.....	None
Sept. 15	4:50	Los Angeles.....	34°03'	118°15'	2	3	.....	None
Sept. 16	22:20	Lakeport.....	39°03'	122°56'	3	1	5	None
Sept. 18	3:45	Los Angeles.....	34°03'	118°15'	3	1	3	None
Oct. 4	5:21	Eureka.....	40°48'	124°10'	2	1	3	None
Oct. 4	20:46	Eureka.....	.....	.....	4	1	4	None
Oct. 5	11:04	Salinas.....	36°41'	121°40'	5	1	20	None
Oct. 5	11:04	Spreckels.....	36°38'	121°38'	5	4	10	Faint
Oct. 5	11:05	Los Gatos.....	37°12'	121°58'	3	1	.....	None
Oct. 5	11:05	San Jose.....	37°15'	121°53'	3	1	4	None
Oct. 5	11:07	San Francisco.....	37°48'	122°26'	4	1	1	None
Oct. 6	21:33	San Francisco.....	.....	.....	3	1	4	None
Oct. 12	9:45	Warner Springs.....	33°15'	116°45'	7	1	2	Rumbling
Oct. 12	9:48	Aguanga.....	33°30'	117°00'	5	1	2	Rumbling
Oct. 12	9:48	San Diego.....	32°43'	117°10'	3	1	30	None
Oct. 12	9:51	Hemet.....	33°45'	116°45'	3	1	2	None
Oct. 12	9:58	Calexico.....	32°41'	115°30'	3	1	30	None
Oct. 30	22:32	El Centro.....	32°50'	115°35'	2	2	1	Faint

TABLE I.—NON-INSTRUMENTAL EARTHQUAKE REPORTS, CALIFORNIA, 1920.—*Cont.*

DATE 1920	Approx. Time 120th Mer.	STATION	Approx. Lat. (N.)	Approx. Long. (W.)	Intensity R-F	Number of Shocks	Duration Seconds	SOUNDS
	H. M.							
Oct. 30	22:37	El Centro.....			3	1	.....	Faint
Nov. 30	17:30	Maricopa.....	35°04'	119°24'	4	1	10	None
Nov. 30	17:30	Taft.....	35°07'	119°26'	5	1	10	None
Dec. 4	3:55	Los Alamos.....	34°45'	120°15'	4	1	.....	None
Dec. 5	4:03	Maricopa.....	35°04'	119°24'	4	1	10	None
Dec. 5	4:03	Ojai.....	34°25'	119°12'	5	1	1	Faint
Dec. 5	4:03	Santa Barbara.....	34°23'	119°40'	5	1	10	None
Dec. 6	.....	San Luis Obispo.....	35°13'	120°45'	3	1	.....	.....
Dec. 13	9:37	Lone Pine.....	36°37'	118°01'	4	1	.....	Rumbling
Dec. 14	19:45	El Cajon.....	32°48'	116°58'	3	1	.....	None
Dec. 14	19:57	Ocean Beach.....	32°45'	117°15'	3	1	.....	None
Dec. 14	19:57	Point Loma.....	32°43'	117°15'	3	1	.....	None
Dec. 14	19:57	San Diego.....	32°43'	117°10'	3	1	.....	None
Dec. 18	9:26	Hemet.....	33°46'	116°58'	5	2	10	Loud
Dec. 18	12:30	Spreckels.....	36°38'	121°38'	3	1	2	None
Dec. 19	4:15	Spreckels.....			3	2	3	None
Dec. 19	20:30	Brawley.....	32°59'	115°40'	4	2	5	Rumbling
Dec. 19	21:15	Amos.....	33°05'	115°16'	5	2	.....	Rumbling
Dec. 19	21:15	Blythe.....	33°35'	114°38'	3	1	.....	None
Dec. 19	21:31	Calexico.....	32°41'	115°30'	2	1	15	None
Dec. 20	6:46	Brawley.....	32°59'	115°40'	3	1	.....	.....
Dec. 20	6:46	Calexico.....	32°41'	115°30'	3	1	45	None
Dec. 20	7:15	Blythe.....	33°35'	114°38'	3	1	.....	None
Dec. 20	10:00	Amos.....	33°05'	115°16'	3	1	.....	None
Dec. 21	6:45	Brawley.....	32°59'	115°40'	3	1	.....	.....
Dec. 21	6:48	Calexico.....	32°41'	115°30'	3	1	30	None
Dec. 21	7:15	Blythe.....	33°35'	114°38'	4	1	.....	None
Dec. 21	7:40	Blythe.....			4	1	.....	None
Dec. 21	7:00	Amos.....	33°05'	115°16'	4	1	.....	None
Dec. 21	11:55	Salinas.....	36°41'	121°40'	3	1	3	None
Dec. 21	11:55	Spreckels.....	36°38'	121°38'	4	3	20	None
Dec. 21	20:18	Spreckels.....			4	1	5	Rattling
Dec. 29	2:15	Willows.....	39°37'	120°31'	5	1	.....	None

ON A PIEZO-ELECTRICAL ACCELEROGRAPH

By HARRY O. WOOD

It was the purpose of a recent study¹ to detect, and to register, vibrations in earth theoretically like earthquakes, but with periods much shorter than in ordinary local earthquakes, and with amplitudes far smaller, even approaching molecular magnitudes. In this work a method was employed which is substantially new, both in fundamental principle and in assembly of auxiliary apparatus. In both respects the method requires further development. But ultimately it will prove valuable for seismometric studies. Therefore an account of it is warranted now, simple enough and in sufficient detail to make the entire method clear to all who work with seismographic mechanisms.

As its development proceeds the method will be greatly improved. But this is work for physicists proficient in electrical theory and in the design and manipulation of apparatus for physical research. Therefore, though in a sense this is only a preliminary paper, the present writer does not expect to do further work on the development of the method.

This method was first employed and described by Prince B. Galitzin.² The work of this investigation was completed before the more complete paper by Galitzin became available, but his briefer notes in the *Comptes Rendus* were seen, and these led to this study. His work was addressed primarily to physicists, and tacitly requires knowledge of physical crystallography and of physical instruments for research of comparatively recent invention. It is based upon electrical phenomena and electrical methods ordinarily unfamiliar to workers in

¹ In the conduct of this work the writer received substantial assistance from a large number of colleagues. He is especially indebted to Dr. W. F. G. Swann, and to Dr. W. G. Cady, for help with the fundamental part, and to Mr. B. McCollum and his associates, Dr. E. A. Eckhardt and Mr. O. S. Peters, for help with the auxiliary apparatus. In the mechanical designing, and in other ways, Mr. E. C. Crane rendered valuable assistance.

² Galitzin, Prince Boris, "An Apparatus for the Direct Determination of Accelerations," *Proceedings of the Royal Society*, A, 95, July 15, 1919, translated from *Bulletin of the Academy of Sciences of Petrograd*, 1915; also brief notices in *Comptes Rendus*, 1915, "Description d'un appareil destiné à la détermination direct des accélérations," and "Mesure direct des accélérations."

seismology. Consequently, to make the fundamentals of the method sufficiently clear a brief exposition of the phenomena of piezo-electricity is required, for on this the method depends.

PIEZO-ELECTRICITY

Though it may have been known earlier in a vague way, in a definite sense piezo-electricity was discovered about 1880 by the brothers, Jacques and Pierre Curie. Since then it has been known that many crystalline substances react, a few very sensitively, to very minute pressures, or tractions, or shears—forces, in short—when these are applied along certain definite directions through the crystalline structure. Electric polarization, with the accumulation of electric charges, results. For the same applied force the amounts of these charges vary greatly with different substances, sometimes greatly with different directions through the same substance, but they are never large, and in most instances they are extremely small. So, until very recently, hardly any attempt has been made to utilize piezo-electricity for any practical purpose, though the Curies, in their investigation of it, pointed the way by devising a balance, a manometer, and an electrometer dependent upon it.

Galitzin turned to this property in an effort to obtain a direct measure of the *acceleration* of vibratory motion. The mass of a pendulum (suspended by a spring-hinged rod) was made to rest with a small, determinate, initial pressure against a buttressed plate of quartz. The amount of the pressure was determined and controlled by the angle of inclination of the ballistic pendulum thus formed. The surfaces of the quartz plate were coated with metallic films. These served as electrodes. One was connected to earth, the other to a string electrometer. Vibratory motion then caused variation in the pressure exerted by the ballistic mass on the quartz plate, and this produced variation in the electric polarization of the quartz, and so in the accumulated electric charges. These in turn caused excursions of the string of the electrometer which were photographed on a sensitized strip reeled at a uniform rate in the direction at right angles to the shifting of the string. Even in so primitive a set-up as this, high sensitiveness was obtained and, with suitable precautions, much reliability.

In order to discuss the present investigation intelligibly, for the special group it is intended to reach, it appears necessary to consider the phenomena of piezo-electricity in some detail—all the more since all ordinary treatments of this subject deal almost exclusively with the-

oretical considerations in physics and crystallography, and only in vaguest terms with any aspects of its practical utilization.

Crystallized matter is distinguished by orderly and essentially invariable space-distributions of its planes of growth and cleavage, and of its other physical properties, in specific space-arrangements which exhibit planes and axes of symmetry, as precisely defined for crystallography, and sometimes a center of symmetry also. These space arrangements possess different degrees of symmetry; in brief, on this basis crystallized matter is found to divide into thirty-two classes,³ each characterized by a definite degree of symmetry, considered due to different groupings of molecules, or, better, atoms, in space arrangements called space-lattices.

In twenty of these crystallographic classes no center of symmetry is found, the classes technically designated in the older and more widely known nomenclature as hemimorphic, hemihedral, and tetrahedral.

In these classes, in general, opposite ends of a line or direction, or lines or directions, through the crystalline medium are not characterized by the same grouping of planes or association of physical properties; in a word, these directions are polar. So all matter whose crystalline structure is lacking in a center of symmetry has at least one direction, and usually many, with two or more principal directions, along which the application of a force, as pressure or traction, will produce electric polarization with the accumulation of electric charges of opposite sign at opposite ends. In most instances this effect is extremely small. But with a few substances it is appreciable, and in a very few, in Rochelle-salt notably, this effect is very much greater for some directions than for others.

Further, when there are two or more directions through a substance which are principal axes of piezo-electricity, it happens that the application of force along one direction may produce perceptible polarization not only at the extremities of such a line but at the extremities of another, also. This is so with both quartz and Rochelle-salt. This condition makes it possible to apply variations in force in one direction through the crystal substance and to accumulate resultant charges upon planes at right angles to another direction, and it happens that this is the efficient way to produce and utilize this effect.

³ These classes are commonly grouped in six, or seven, systems according to the defined axes to which these geometrical arrangements are most naturally and easily referred.

In seeking piezo-electric effects caused by vibration of exceedingly small amplitude Rochelle-salt was utilized: so, in due course, the case must be discussed for this substance. But it will be of advantage for simplicity and clearness to lead up to this by a discussion of the case for quartz, in which the crystallographic symmetry relationships are less complicated and easier to visualize geometrically. Moreover, for use in seismology quartz may possibly be found to serve better than the more sensitive Rochelle-salt.

QUARTZ

Equally developed crystals of quartz appear as hexagonal prisms terminated by hexagonal pyramids at both ends. Study of the physical properties, however, and of the crystal planes, too, shows that this is merely a resemblance, that in reality there are four groups of crystal planes, or crystal forms, in equilibrated combination, two balanced complementary rhombohedrons forming the termination planes, and two balanced complementary trigonal prisms forming the vertical, or prismatic, bounding planes. Both sets of groups of planes are referred to the same crystallographic axes, usually chosen in American crystallographic practice as three alike in the horizontal plane, or prismatic zone, perpendicular to the prism faces and at 60° with each other, with opposite properties at opposite ends, and one, the so-called optical or principal axis, vertical, unlike the others, with like properties at both ends.

Therefore, the principal axis in quartz is not an axis of piezo-electricity. Force exerted in its direction produces no polarization.

On the other hand, the three horizontal directions which bisect the angles between the horizontal crystallographic axes are the chief axes of piezo-electricity. They emerge as bisectors of the angles between the prism faces. Force applied as pressure or tension upon planes cut perpendicular to any one of these intermediate directions develops electric polarization and the accumulation of charges whose quantities are given by the formula

$$q = DF \quad (1)$$

where q = quantity of electricity in electrostatic units, e. s. u.

F = total effective force applied, measured in dynes.

D = the piezo-electric "constant," an empirical coefficient of the piezo-electric effect reduced from observation and experiment, and found somewhat variable with some substances.*

But, now, if we compress or dilate a crystal plate cut from quartz in a direction perpendicular to both the principal crystallographic axis

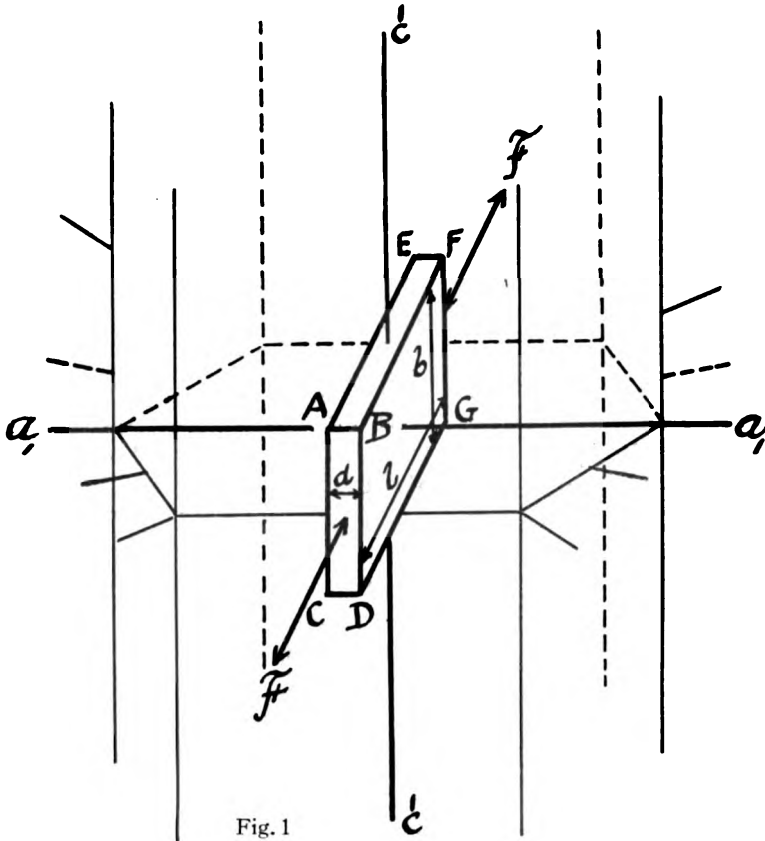


Fig. 1

c and to any one of the piezo-electric axes, thus applying the force upon the planes $A B C D$ and $E F G$ (Fig. 1) electric polarization[†] is produced with reference to the piezo-electric axis a_1 . In this case, however, the quantity of electricity thus set free is given by the formula

*For quartz the Curies found, for the chief directions, $D = 6.32 \times 10^{-8}$ e. s. u. of quantity per dyne.

†The electricity thus set free and accumulated is opposite in sign to that which would be produced by force similarly applied directly upon these faces.

$$q = D \frac{l}{d} F \quad (2)$$

where l is the length of the plate and d its thickness measured in centimeters, and when, as before, $D = 6.32 \times 10^{-8}$, the piezo-electric "constant" found by the Curies.

As a result of extended investigations with quartz and other piezo-electric substances, the Curies were able to state the following laws:

1. The quantities of electricity set free at the end of an axis due to a deformation are equal and of opposite sign.
2. The quantities of electricity set free at one of the ends of an axis are equal and of opposite sign for two deformations inverse in sense to each other.
3. The quantities of electricity set free on each end are proportional to the variation in force applied.
4. For one and the same variation in force applied, exerted in the direction at whose extremities the electricity is collected, the quantities of electricity set free are independent of the dimensions of the crystal.
5. For one and the same variation in pressure, exerted normal to the direction along which we collect the electricity, the quantities of electricity set free are proportional to the ratio of the length to the thickness; they are independent of the third dimension.

And these lead, together with the phenomena of pyro electricity, to the supplementary generalizations:

6. For one and the same crystal the quantities of electricity set free are proportional to the intensity of deformation at each point.
7. For one and the same intensity of deformation at each point, the quantities of electricity set free are proportional to the surface upon which the electricity is collected and are independent of the third dimension of the crystal.

These laws plainly teach that when there is only a given total quantity of force to be applied, and only a given volume of the crystallized substance also,

(a)* When the charge is collected upon planes perpendicular to a piezo-electric axis, which is parallel to the direction along which this

* In this case we may alter the dimensions of the crystal plate, but in so doing, if we decrease the collecting area, we increase the force applied per unit of area, and so the intensity of deformation at each point, in equivalent ratio, and *vice versa*.

force is applied, we will obtain a given quantity of liberated electricity dependent only upon the total amount of the force applied; but

(b) When the charges are collected upon planes perpendicular to a piezo-electric axis which is perpendicular to the direction along which the force is applied, there will be obtained a given quantity of liberated electricity dependent both upon the total amount of the force applied and also upon the ratio of the length of the crystal plate to its thickness.

Therefore, in this second case, which permits a more efficient utilization of force, it is advantageous to cut the material so that, for a given volume, the crystal plate shall be as long and thin (and therefore as narrow, too) as the requisite mechanical strength, stiffness, and electrical requirements will allow. This latter condition enters because such crystal plates, acting primarily as gatherers or generators of electricity, act secondarily at the same time as electrical condensers, as the charge is set free by action of force and accumulated on the electrodes, so that the shape cannot depart too far from a thin, flat plate without loss of advantage. The shape specified allows, for a given total of force, a maximum force-effect per unit of cross-section, thence a maximum intensity of deformation for a given collecting area (or, conversely, a maximum collecting area for a given intensity of deformation) and so a maximum liberated charge.

Of course mechanical considerations, especially with such fragile, brittle, and perhaps flexible, substances as Rochelle-salt, forbid indefinite reduction of thickness and width, or indefinite increase in length; and electrical conditions, since there is dependence upon a condenser effect, as well as upon the piezo-electric liberation of charge, require the width to be at least twice as great as the thickness, and preferably more.

ROCHELLE-SALT

The case for Rochelle-salt closely resembles that for quartz but is not wholly identical with it. Rochelle-salt crystallizes in the hemihedral, as distinguished from the hemimorphic, class of the orthorhombic system. That is, Rochelle-salt crystals possess the symmetry of a class in which the crystal planes are referred to three axes at right angles to each other, but in which the planes of the simplest and predominating prismatic and pyramidal bounding surfaces, the so-called unit crystal forms, in their ideal, equilibrated development, intercept these axes at different distances from the common center of axes, so that, in crystallographic language, the unit distance is a different magnitude on

each axis. This class also has no center of symmetry. Consequently the two ends of each principal axis, or of any direction through the crystal, are unlike in respect to physical properties. Therefore, each crystallographic axis is a piezo-electric axis.

Neglecting minor modifying planes, or crystal forms, Rochelle-salt crystals develop as unit orthorhombic prisms terminated by base planes which stand at right angles to the planes of the prismatic zone, as in Figure 2, where the axes are as shown: c , vertical; b , horizontal; and a , horizontal; all perpendicular to each other.

Since all three of the principal axes are polar, there are many

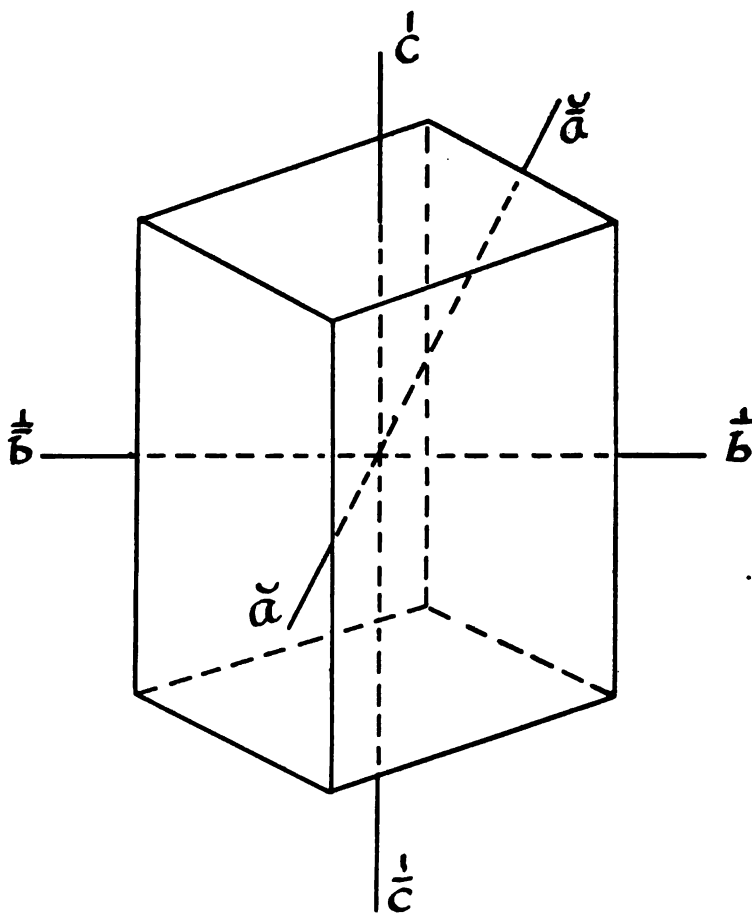


Fig. 2

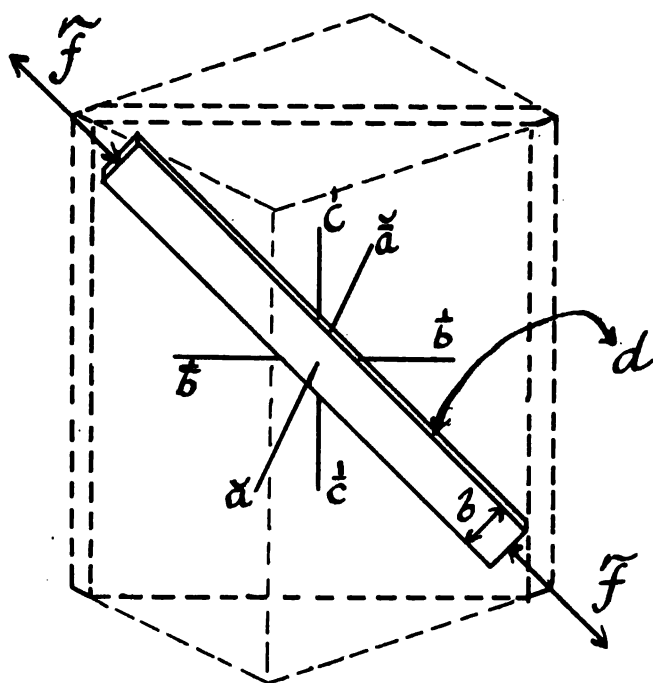


Fig. 3

ways in which plates could be cut from crystals of Rochelle-salt to yield piezo-electric responses to applied forces. The most efficient of these is considered to be as follows: a thin plate (of thickness d) is cut out of the crystal with its flat sides perpendicular to the $\hat{a}$ axis, and parallel, therefore, to the $\hat{b}$ and $\hat{c}$ axes. Then from this plate a long narrow strip (of length l and breadth b) is cut so that its sides are at angles of 45° with the $\hat{b}$ and $\hat{c}$ axes, Figure 3. The flat sides of this strip are covered with metallic film electrodes of appropriate area and electrical connections, as developed below; and the varying force to be detected or measured is applied as pressure or tension at the end cross-section ($b \times d$). Under these conditions a value for the piezo-electric "constant" is found, $D = \delta_{14} = x \times 10^{-5}$. It is noteworthy that this value of the piezo-electric coefficient is of the order of a thousand times the value of D in Rochelle-salt itself when the force is exerted in directions parallel to the crystallographic axes.

The quantity of electricity set free by a force of F dynes, applied as specified to such a plate-strip, is given by the formula,

$$q = D/2 \times l/d \times F \quad (3)^7$$

It is worthy of note in passing that the force is applied as specified not in order to produce simple compression and dilatation along the length of the strip but rather to effect shearing⁸ in which there is set up a tendency for the crystal layers to glide over each other in the direction of the $\hat{b}$ axis perpendicular to the $\hat{c}$ axis. This shearing, which could, of course, be produced in other ways than by force applied at 45° as indicated above, by torsion, for example, produces a maximum electrical polarization at opposite ends of the $\hat{a}$ axis, to which the flat sides of the strip are perpendicular. Nevertheless, for convenience, throughout the discussion which follows, the applied force is considered to produce pressure, or tension, and consequent linear deformation.

From the formula (3) which applies in this case, it is seen that, as in the more efficient of the arrangements with quartz, the quantity of electricity set free depends upon the ratio of l to d . And as with quartz, for a given force per unit of cross-section this is independent of b which, however, for reasons of electrical capacity, must be greater than d , and for mechanical reasons also, since some stiffness is required. But b should be no greater than these requirements make necessary, because, for efficiency, the greatest possible intensity of deformation must be produced with a given total of force, which, in the investigation under discussion, was always small. For a given volume of crystal, then, d should be made as small as practicable, b no larger than necessary, and l , therefore, as long as the conditions allow. In fact l should be as long as mechanical and crystal considerations will permit in all cases where the applied force acts freely until arrested and balanced by the elastic deformation of the crystal. Should the range of action of the force be limited by other considerations, such as the amplitude of the vibratory motion, theoretically l might not need to be longer than some certain value, such that Δl , the change in length produced by the force, might just equal the total range of the force in

⁷The numeral 2 appears in the denominator of this fraction, differing thus from the formula for quartz, on account of the 45° angle made by the sides of the strip with the $\hat{b}$ and $\hat{c}$ axes.

⁸"That is to say, in order to produce an electrification along the $\hat{a}$ axis of the crystal, the planes normal to the $\hat{c}$ axis must be sheared over one another in the direction of the $\hat{b}$ axis."

amplitude. But this is in anticipation, and as will appear below, it is a contingency that in fact needs no further notice.

In any case a given volume of crystal should work most efficiently when shaped in accordance with the stated considerations. Though in different cases different volumes of crystal may be chosen for use, still, because crystals cannot practicably be grown indefinitely large, as well as for mechanical and electrical reasons, these cannot be indefinitely large or small. There is, practically speaking, an optimum volume. Since thus far plates of rather short⁹ length only can be cut from crystals at best, this optimum is larger than the maximum volume so far obtainable. Its strict limits must be determined by future work. It will be found convenient for our mathematical uses to employ the formula for volume which is given below.

A varying force applied at the ends of such a plate sets free electric charges which alternate in sign as the direction of the force changes successively. Thus, in a sense, electrically the plate acts as a generator, and these charges collected on the metallic electrodes may be allowed to leak off through a metallic circuit, such as a string galvanometer and leads, thus generating a feeble alternating current, or one side of the plate (or condenser-system) may be connected to earth and the other led to an electrometer, preferably a string electrometer, or into the grid of an audion bulb, when a measure or utilization of the potential is obtained.

Also, electrically, the metallic-coated crystal plate forms a leaky condenser, or in practice with long plates, a group of condenser elements, where discontinuous strips of metallic film of equal length l are applied opposite to each other on the sides of the plate.

When it is desired to convert the charges into current, as with the string galvanometer, it is found that all of the electrodes on each side of the plate should be joined together (or each side should be covered with a continuous metallic film), so that there is formed thus either a group of condensers connected in parallel or a single condenser.

On the other hand, if it is desired to measure or utilize the potential developed, which then should have the maximum value practicably

⁹ Since plates could not be obtained so long as were desired by cutting from complete crystals, at the writer's suggestion Mr. Alan Leighton of the Bureau of Mines, under the direction of Mr. George S. Rice, Chief Mining Engineer, undertook the development of a method of growing very long, thin, flat plates of proper crystallographic orientation. He succeeded in demonstrating the practicability of this.

attainable, the first requisite is to determine the electrical capacity of the external circuit leading to the electrometer string or audion grid, and then to cover the opposite flat sides of the crystal plate with discontinuous metallic electrode films connected in series and so proportioned that the crystal condenser system as a whole, given by the formulas,

$$C_{c_1} = C_{c_2} = \dots C_{c_m} = KA/4\pi d \quad (4)$$

and
$$C_o = \frac{1}{m} C_{c_m} \quad (5)$$

shall be equal to the external capacity C_o .

The latter case is the more important and requires analysis along the following lines. Suppose mn electrodes to be applied on each side of one long, narrow, thin plate of crystal; as indicated in Figure 4, each electrode l centimeters long and b wide, so that the plate may be con-

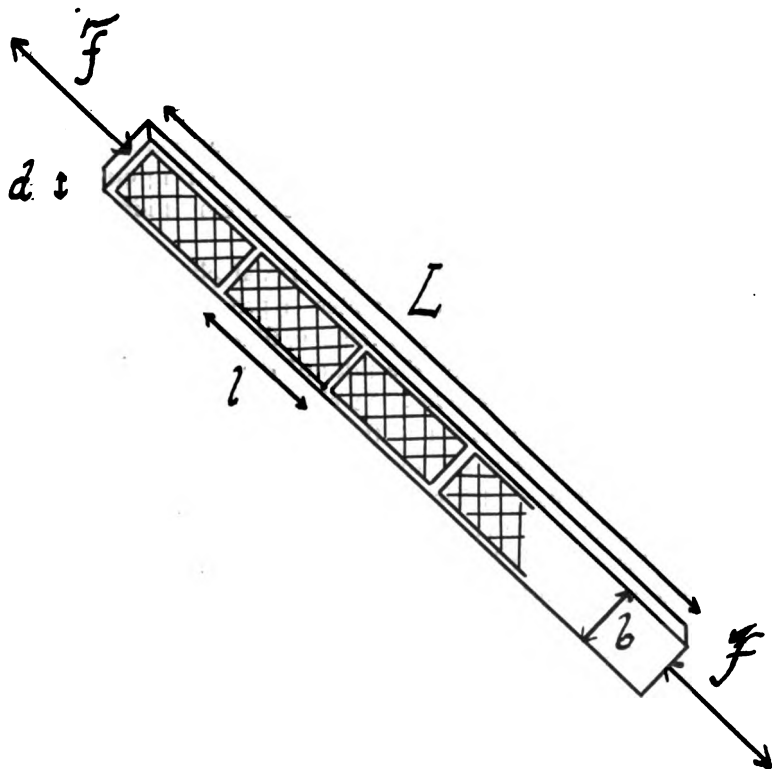


Fig. 4

sidered as made up of mn elements of crystal each $l \times b \times d$, in perfect end-to-end contact. These, now, might be connected all in series ($n=1$), or all in parallel ($m=1$), or in n groups in parallel with each group made up of m elements in series.

The volume of such a plate obviously is given by the formula

$$V = m n b d l \quad (6)$$

The electrical quantity for any element is $q_1 = D/2 \times l/d \times F$ e. s. u. If now m of these are joined in series $q = D/2 \times l/d \times F$ also, for when capacities are coupled in series $q = q_1 = q_2 = \dots q_m$. But if, further, n elements joined in parallel, or n groups (of elements joined in series) joined in parallel, are taken, each group having either (1), or any number up to m connected in series (but better m to keep the analysis general in form), then

$$q = n \times D/2 \times l/d \times F \text{ e. s. u.} \quad (7)$$

The potential is given by the formula

$$e = q/C \text{ e. s. u.} = e = 300 q/C \text{ volts} \quad (8)$$

where C equals the total capacity, that is, the capacity of the crystal plus the capacity of the external insulated system—the leads and electrometer string, for example—whence

$$C = C_c + C_e \quad (9)$$

$$C_c = KA/4\pi d$$

$$C_c = Kbl/4\pi d$$

and for n groups of elements, (C_c), connected in parallel with m elements in each group connected in series

$$C_c = n/m \times Kbl/4\pi d \quad (10)$$

whence

$$e = \frac{\frac{n \times D \times l}{2 d} F}{\frac{n \times Kbl}{m \times 4\pi d} + C_e} \quad (11)$$

It is desired to obtain a maximum value of e from a crystal plate limited in volume, $V = mndbl$. The total length of the plate obviously is $mnL = L$. Substituting for l in equation (11)

$$e = \frac{\frac{DL}{2md} F}{\frac{KbL}{m^2 4\pi d} + C_e} \quad (12)$$

From electrical considerations this will be a maximum when the capacity of the crystal condenser system equals the capacity of the external electrometer, or audion-grid, system.

Hence

$$\begin{aligned} e_{\max} &= \frac{\frac{D L}{2md} F}{\frac{2KbL}{m^2 4\pi d}} \\ &= \frac{m\pi D F}{Kb} \end{aligned} \quad (13)$$

This requires b to be as small as its electrical capacity relation to d , and considerations of mechanical strength, permit; m , the number of elements connected in series, should be as large as the dimensions of the crystal and concomitant capacity relations permit. With L , b , d , and $C_e = Kbl/m^2 4\pi d$ fixed, m , and l , are also fixed by the following relation,

$$\begin{aligned} C_{e_1} &= C_{e_m}, \quad C_e = C_{e_m}/m = C_e = Kbl/4\pi d \\ l &= \frac{4\pi C_e}{K} \times d/b \times m \end{aligned} \quad (14)$$

This formula allows the number, m , and the size, $l \times b$, of the elementary capacities, C_{e_1} , to be approximated. Since l increases with m , though it should be as large as practicable, it cannot be made very large unless a large $L = ml$ can be made available. The quantity n disappears from the analysis above, that is, in an endeavor to increase the resulting potential, there is no advantage in connecting the crystal electrodes in parallel. This is confirmed by other lines of analysis omitted here.

When e is a maximum $m = \sqrt{[Kbl/4\pi d C_e]}$, whence $e \propto m$ and $e \propto \sqrt{L}$: substituting

$$\begin{aligned} e_{\max} &= \pi D \sqrt{\frac{L}{4\pi C_e K b d}} \times F \text{ e. s. u.} = 300 \pi D \sqrt{\frac{L}{4\pi C_e K b d}} \times F \text{ volts} \\ &= \frac{300 \pi}{\sqrt{4\pi K C_e}} \times \sqrt{\frac{L}{b \times d}} \times D \times F = \chi \times \xi \times D \times F \text{ volts} \end{aligned} \quad (15)$$

For Rochelle-salt $\chi \propto 1/KC_0$, determinable by measurement,
 $K \approx 80$, a "constant" measurable in any particular case,
 $C_0 \leq 10$, subject to control and measurement,
 $\xi \propto \sqrt{L/(b \times d)}$, dependent only on the dimensions of the crystal plate and subject to control in preparation,
 $D = x \times 10^{-8}$, [$x > 1$] determinable by measurement.

The above (15) is a formula which permits computation of the maximum potential theoretically derivable from a Rochelle-salt crystal plate when subjected to a definite force. This maximum value never can be realized in practice, owing to mechanical and electrical losses and counter-effects which will be mentioned in appropriate sequence below.

The investigation under consideration was made under conditions unfavorable to precise experimental control. On this account numerous reasonable assumptions and approximations were made between limits, and these assumed and approximated ranges give rise to considerable ranges in the results obtained. Under these conditions a realizable efficiency of 5 to 45 per cent of the theoretical maximum was indicated. Under better control of conditions more precise determinations, and probably higher efficiency and a more determinate value for it, can be obtained.

All the foregoing is on the basis of theory. It neglects modifying factors due to other physical properties, and idiosyncracies of behavior in piezo-electric substances and in Rochelle-salt in particular.

As an actual material, despite its extraordinary sensitiveness for detecting changes in applied force, Rochelle-salt possesses properties which constitute drawbacks to its use.

There is one group of properties which render it mechanically much less suitable for rough practical use in the field than quartz, for example.

It is fragile and brittle; thus the sensitive element is liable to injury and destruction not only as a whole but especially at the contact surfaces, the end cross-sections, upon which the variable force is applied. This is all the more true because these have to be small for theoretical reasons. It is readily soluble in water. It melts at a little

over 70° C. Flaws are often found in the crystal as a condition of growth. It contains water of crystallization.

Another group of the properties of Rochelle-salt affects its electric and piezo-electric behavior, modifying this and leading to different results (1) with different crystal plates used under the same conditions, and (2) with the same crystal plate under different conditions, showing inconsistencies, and even, apparently, (3) with the same crystal plate under apparently identical conditions at different times. As a result of these vagaries, the piezo-electric responses of Rochelle-salt to applied force were found quite variable, and also smaller than the calculated values. For these reasons it does not yet afford a method for measuring force, or acceleration, precisely.

In the theoretical calculations, as we have seen, there enter two "constants," or numerical coefficients, determined by experiment. These are the dielectric constant, K , and the piezo-electric constant, D . It must be kept in mind that D varies with different directions in the crystalline medium and that we are chiefly concerned with a particular value of D , δ_{14} , the value when plates are cut and force is applied as specified above. There also will be occasion to use in calculation the value of Young's modulus, E , for the given conditions.

Regarding the value of Young's modulus, quoting a manuscript report made on this by Professor W. G. Cady, "Young's modulus was measured for a thin rod of Rochelle-salt oriented as above by Professor Barus in Providence, using a steady pressure and an optical interference method. The value obtained, which was only a rough approximation, was of the order of 10^{11} . Later the writer measured the distance between nodes of longitudinal stationary waves in a long, narrow plate, and found, for a frequency of 100,000, a wave-length of approximately 4.8 cm. Hence the velocity of sound in Rochelle-salt, at least for long, narrow plates cut as indicated, is about 4.8×10^6 cm./sec., and since the density is 1.76 it follows that Young's modulus is about 4.06×10^{11} for high frequency vibration."

Now it is obvious that when force is applied to the crystal plate, either as a pressure or as a tension, it compresses or stretches this as an elastic solid. But in addition to this it sets free an electric charge

$$q = D/2 \times l/d \times F,$$

which must be removed if the faces are to be kept at constant potential, say the potential prior to the application of the force. Unless the

charge is removed the force is not wholly used up in doing the mechanical work; for part remains available as accumulated electricity. But, unless removed, this accumulated charge acts to maintain a counter effect resisting change in length, in addition to the ordinary elastic resistance. For, if a difference of potential, e , be imposed upon the the opposite faces of the crystal plate, a force

$$f = E/2 \times Dbe$$

will have to be brought into play in order to prevent the crystal from changing in length. Hence, unless the charges are removed instantaneously, the crystal will behave, instantaneously at any rate, as a stiffer substance than if it were not piezo-electric. That is,

$$q = D/2 \times l/d \times (F - f).$$

However, the value of E given by Cady was a value determined under the actual conditions of use at high frequency; that is, with the piezo-electric effect present and active. While, therefore, it may be too high for low frequency conditions, it is only four times greater than the rough approximation made by Barus with a condition of steady pressure.¹⁰ Consequently, no significant error will be made in taking $E = 4 \times 10^{11}$, especially if the value $E = 10^{11}$ is kept in mind and applied as a lower limit for this constant.

Hence, while it is obviously true that only a portion of the force becomes available as electric charge, what really is sought is what portion of this theoretical electric charge becomes available practically for detecting and recording varying force effect. The theoretical development given above is not concerned with the total effect of the force, but only with its charge-producing effect. This is explicitly provided for in the factor, D , the piezo-electric "constant," and also in the factor, K , the dielectric constant, both of which, with Rochelle-salt, require experimental checking in each set-up.

For the value of the dielectric "constant" given in tables hitherto published—6.7 to 8.9, for example—is greatly in error according to the findings of Anderson and Cady. The latter in his manuscript report states: "The dielectric constant of Rochelle-salt, measured at high frequency, is of the order of 80, but it is apparently dependent on me-

¹⁰ I do not know whether Barus had the sides of his rod electrically connected to remove accumulated charges.

chanical pressure and other factors." Anderson obtained values of over 100 for this constant, according to information communicated by Cady. Hence, though this coefficient is not strictly constant, and though, indeed, variation in capacity of the crystal member due to changes in the dielectric constant, occasioned by variation in pressure, was suggested at an early stage of the work as a likely way of detecting pressure changes,¹¹ nevertheless the departure from the value 80 is not certain enough nor great enough to warrant taking it into account in theoretical computations. Cady later wrote: "I use the value 80 as a sufficient approximation for all frequencies." Hence, throughout the recent investigation K has been taken as 80. If it is larger, C_e becomes larger and the electrical efficiency of the assembly is reduced, and this remains true also if it is smaller, since $C_e = C_o$ is the optimum electrical condition.

With regard to the piezo-electric "constant," D , or δ_{14} , under the conditions of the problem, this was long since given by Pockels as 10^{-8} with the accompanying comment that this value was a lower limit only, for Rochelle-salt cut and used as specified. For quartz cut and used in the best way, $D = 6.32 \times 10^{-8}$. The respective formulas for quantity are

$$q_a = 6.32 \times 10^{-8} \times l/d \times F$$

$$q_{rs} = \frac{x \times 10^{-8}}{2} \times l/d \times F.$$

If F and l/d are the same in both cases,

$$q_{rs}/q_a = 80 \ x.$$

Therefore, at minimum, Rochelle-salt is at least eighty times as effective as quartz, theoretically. Further, according to Cady's manuscript report, values for δ_{14} found by experiment vary between 3.4 and 40 times 10^{-8} , and a further report gave the results now quoted: "The piezo-electric constant of six crystals was measured with the ballistic galvanometer method. Each crystal had previously been placed in a dry atmosphere for twenty-four hours and the temperature regulated to 20° C. Under these conditions quite consistent results were obtained. We found that the value δ_{14} varied between 4 and 12 times 10^{-8} c. g. s. e. s. units" Nicholson¹² obtained values for D under other

¹¹ This suggestion was soon withdrawn.

¹² "The Piezo-electric Effect in the Composite Rochelle Salt Crystal," Nicholson, A. McL., *Trans. A. I. E. E.*, p. 1319, October 9, 1919.

conditions of use varying between one and twenty times 10^{-5} . Taking these several values for x , namely 3.4, 4, 12, 20, and 40, the theoretical superiority of Rochelle-salt over quartz is, respectively, approximately 270, 320, 960, 1600, and 3200 times. Therefore, there should be no error on the side of exaggeration if we consider Rochelle-salt piezo-electric detectors theoretically from say 250 to 1500 times as sensitive as quartz, when F and l/d and optimum electrical capacity relations are the same in both cases. An unlikely minimum is 80 times, when x equals 1.

Hence the theoretical electric charge will lie between limits, determined by substitution in the formulas given above of the extreme allowable values of D and K .

There will then be departures from the theoretical range in the direction of lesser efficiency, owing to the following erratic behavior.

Effects due to Electro-striction. Anderson, in manuscript reports to the National Research Council, stated findings which tend to show that an electro-striction effect of considerable magnitude enters, and modifies the piezo-electric effect. His crystal plates were cut in the way specified above, but were square instead of elongated—that is, l equaled b . He applied pressure in the two directions at right angles to pairs of edges as indicated by $\longrightarrow a$ and $\longrightarrow b$ in his diagram, Figure 5. Crystallographically these directions are theoretically alike and equal responses should be expected. He obtained, however, considerably greater response to pressure in the direction $\longrightarrow b$, as arbitrarily denominated by him, than in the direction $\longrightarrow a$.

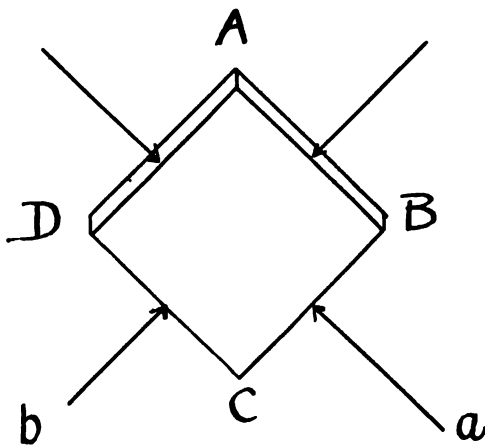


Fig. 5

Also, when he applied an electric field to the electrodes, under restricted definitions carefully stated but of no concern here, he obtained with a ballistic galvanometer, very unsymmetrical responses as charging throws and discharging throws. This dissymmetry of electrical response he ascribed to electro-striction, pointing out that this effect, being irrespective of the direction of charging of the applied field, would act with the piezo-electric effect in one case and against it in the other. But, as a result of his whole study, both of pressure effects and of those produced by the application of a field, he says finally: "That electro-striction plays an important role is quite obvious, both from the present results and from those given (in an earlier report), but the writer has not been able to combine electro-striction and the piezo-electric effect in such a way as to get the results observed here."

A study of this conducted in Cady's laboratory yielded conflicting and inconsequential results.

Therefore, if electro-striction is a factor in this phenomenon, it may sometimes augment and sometimes reduce the electric effects due to pressure, but since D has been determined without regard to it we may neglect it, noting merely that it forbids confident expectation of obtaining the full theoretical charge and potential, and that it forbids employment of the greatest values of D found, since these may have been rendered too large by its action. If, however, the smaller values of D be taken, which may be conditioned by its counter action, the reduction in efficiency from the theoretical values, due to this cause, should be small or altogether absent.

Effects of an applied electric field. Empirical effects in connection with electric fields applied to the crystal electrodes, the cause of which need not be inquired into here, have been noted as follows: Quoting from Cady's manuscript report to the National Research Council, "A . . . plate which had been subjected, while in moist air, to an electric field of 100 volts for two hours, gave, on being connected to a galvanometer, a very considerable deflection even at the end of five hours, like a miniature storage battery. Rochelle-salt shows large dielectric absorption, but not to such an extent as this." And, "When 100 volts were applied for a few minutes to the tin-foil coatings of a plate, the positive terminal being connected to that coating which became positive on application of pressure, it was found that the plate gave exceptionally large throws for several hours afterward, the throws gradually diminishing to their original value. No permanent

improvement resulted. When a potential difference was applied in the opposite direction, the throws decreased. This would suggest that the application of a steady potential difference in the right direction ought to raise the sensitiveness of Rochelle-salt plates. When this was tried at high frequency, however, the results were in all cases negative."

These facts are mentioned, in passing, to indicate some of the difficulties which have hindered the development of this most sensitive vibration-detector into a reliable and precise instrument.

Fatigue, hysteresis, and paralysis. Rochelle-salt crystal plates cut and treated as described above show a decrease in electrical response after a time.¹⁸ This is true also when they are subjected to an applied field. This "fatigue" effect is greater with larger loads and stronger fields. Different crystal plates are affected differently in this respect. Again quoting from Cady's report: "All crystals when subjected for fifteen minutes to a load of 2000 grams showed a decrease in deflections amounting in some cases to 30 per cent. Continued application of this force produced a very marked decrease in the throw obtained in the case of some crystals, while with others very little effect was observed. Some crystals were fatigued by a momentary application of only 1000 grams, while with others only slight fatigue was observed, in both dry and moist atmospheres. The amount of fatigue, as measured by noting the throw on applying the load, after the fatiguing load had been momentarily removed, varied, when the time of fatigue was relatively short, with the magnitude of the fatiguing force. With fatigue of long duration a limit to the amount of fatigue seemed to be approached which was the same for 1,000 as for 2,000 grams.

"At high frequencies, the sensitiveness of most plates seems also to be somewhat reduced under end pressure."

Referring to the effect with an applied field, Anderson stated, "It has been observed that above the field strength of 350 volts/cm. there is a marked effect of hysteresis or fatigue. At these high field strengths, several successive applications of the field produce smaller and smaller effects within certain limits . . ."

McGrath, working with Cady, found that: "When force was applied to the crystal by steps, and then removed by steps, a hysteresis

¹⁸ Nicholson, utilizing Rochelle-salt crystals in a different way, finds that a considerable steady pressure both sensitizes and stabilizes the crystals under his conditions of use.

phenomenon was observed in some cases. This effect has been obtained only with dry crystals."

Babcock, quoting Anderson, in connection with variations in pressure obtained from a mass swinging as a simple ballistic pendulum, wrote: "Other things being the same, the deflections of the string (of the electrometer) are not proportional to the mass M , as, in general, the sensitiveness of a crystal plate is found to be less with heavier loads"; but also "the absolute sensitivity is greater for small loads, but fatigue effects . . . are practically absent at great loads. At these great loads, however, the curves . . . show that the sensitivity is very small, perhaps only a few per cent of what it is at small loads."

Cady and McGrath both point out that continued overload produces temporary paralysis of the electrical activity of the crystal.

The work of Anderson and Cady shows that the sensitiveness in respect to applied force is greatest when, in the case of cross-sections of 1.0×0.1 cm., the plates are subjected to steady initial loads of approximately 200 grams, i. e., about 2,000 grams per square centimeter. Heavier steady loads than this are likely to produce fatigue, or even paralysis, and hysteresis for rapidly varying force-changes, thus leading to reduced efficiency.

Effects of change in temperature. Rochelle-salt as a piezo-electric material appears to be greatly affected by temperature changes. For a plate subjected to momentary impulses of the same amount, Cady found a decrease in electrical response of about 55% for a rise of temperature from 20° to 25° C. and a decrease of nearly 87% for a rise from 20° to 30° C. Further increase of temperature from 30° to 40° C. brought about only slight, practically negligible, further reduction in electrical efficiency. Obviously the responses obtained in practical use of this material will be less than the theoretical values if it is used at a higher temperature than that at which the value of the piezo-electric coefficient has been determined.

Effects of change in humidity. Anderson found that inconsistent results were obtained in measurement unless the crystal plates were dry. He found leakage, presumably surface leakage, with crystal plates not subjected to thorough drying, which leakage disappeared with dryness. However, sensitiveness does not appear to require excessive dryness. Cady reported in this connection: "While the most consistent quantitative results were obtained with plates well dried

with calcium chloride under a bell-jar, still the sensitiveness of plates in all cases observed has always been greater when they were prepared and mounted in a very moist atmosphere. (He was writing in regard to high frequency disturbances where there was scant time for effects of leakage to supervene.—Wood.) Three plates which had given only fair throws were placed for twenty-four hours in air saturated with moisture, after which their throws were approximately doubled. One of these plates while connected to the galvanometer gave a steady deflection, due doubtless to a slight galvanic action. (Similar evidence of a maintained charge has been noted with the string electrometer.—Wood.) Another plate which had been subjected, while in moist air, to an electric field of 100 volts for two hours, gave, on being connected to a galvanometer, a very considerable deflection even at the end of five hours, like a miniature storage battery. . . .”

Since, in this investigation, and in seismic studies, force-changes of fairly low frequency are dealt with, from 1 to 100 cycles per second, or slower pulses still, leakage must be avoided as far as possible. To accomplish this it is necessary to coat thoroughly dry crystals with electrodes, and, when thoroughly desiccated (but not, of course, deprived of water of crystallization) to coat lightly with shellac or paraffin to avoid surface condensation and surface leakage. In this procedure, according to Cady's findings, some sensitiveness would be lost. How far this would impair efficiency with respect to the theoretical value would depend upon the conditions under which the value for D employed was measured.

However, nearly all the erratic behavior of Rochelle-salt described above is in the direction of reduction of efficiency, and the effects obtained in practical use indicate that such a reduction is real, that the effects actually obtained are rarely greater than 25% of those which should follow from theory.

Shortly before I undertook to use the piezo-electric effect in the investigation under consideration a considerable earthquake occurred in Southern California, attended by a train of aftershocks. I immediately suggested to Dr. George E. Hale, then Chairman of the National Research Council, that it was desirable to find if these aftershocks could be detected by the piezo-electric method.

At his request the following experiment was performed by H. D. Babcock at the Pasadena Laboratory of the Mount Wilson Observatory, who soon reported that the method was amply sensitive for

the purpose. Parenthetically, it may be remarked that no earthquake shocks were actually observed or registered by Babcock, who merely established the sensitivity of the method.

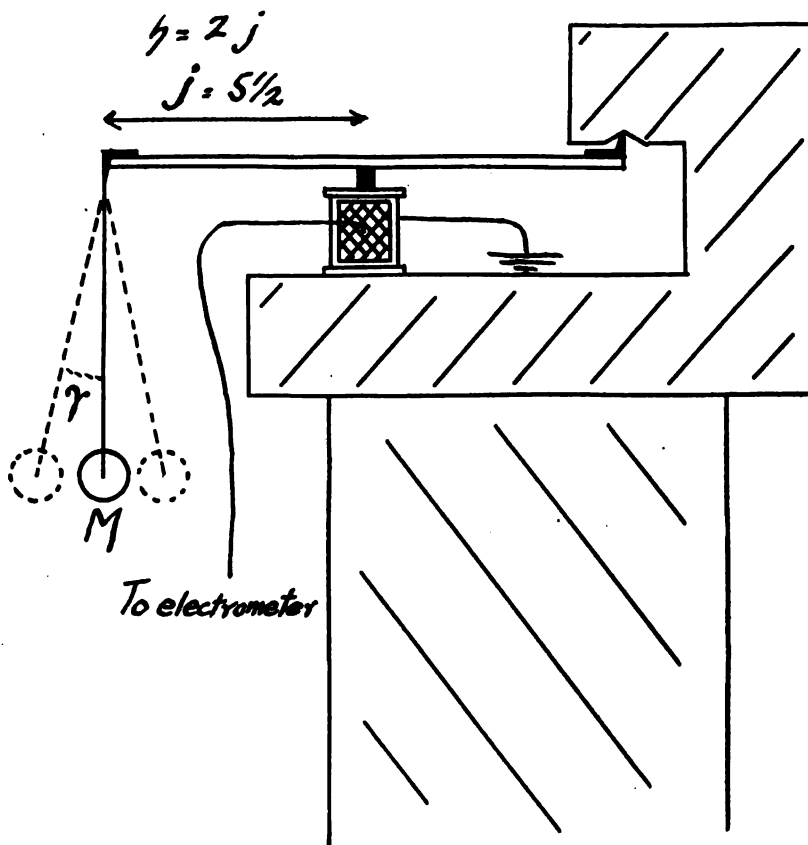


Fig. 6

Abstracting from Babcock's letters to me: "We have made rough tests with quickly constructed apparatus, except that a first-class string galvanometer was used as a detector. A very satisfactory method for getting an idea of the sensitiveness of a crystal plate is shown in the sketch, Figure 6, adapted from Babcock's diagram. Tinfoil electrodes . . . applied . . . to the sides of the crystal plate are connected respectively to the string of the electrometer and to the earth. When the mass M is made to vibrate as shown by the dotted lines (Fig. 6), the string of the electrometer executes a double-period vibration corre-

sponding to the variations in the radial acceleration of M . As M passes through the position of equilibrium, this acceleration is, very approximately,

$$\varphi = 2Mg (1 - \cos \gamma) \times h/j. \quad (16)$$

In one experiment $h = 11$, $j = 5\frac{1}{2}$, $M = 500$ grams, and $\gamma = 5^\circ$. Whence

$$\varphi = 7840 \text{ dynes} \doteq 8000 \text{ dynes.}$$

Under these conditions double deflections of about fifteen scale-divisions in the micrometer ocular of the viewing microscope were observed. [The width of the string permits reading its position to less than one-half a division on the scale.] As to the value of the micrometer readings, the absolute sensitiveness of the instrument is such that one volt gives a deflection of 40 mm. with the apparatus as used for this work, i. e., the 15-mm. deflections correspond to about $\frac{3}{8}$ of one volt."

At this point let it be noted that there was a steady pressure of 500 grams applied on a surface, which, as stated immediately below, was presumably 1×0.1 cm., a steady pressure of 5000 grams per sq. cm., or two and a half times the best initial load.

In his letters Babcock does not state specifically the dimensions of the crystal plate he employed, but his sketches suggest that it was like many of those employed by Anderson, from whom he obtained it, namely, $1 \times 1 \times 0.1$ cm. Nor does he state the electrostatic capacity of the electrometer string and the insulated lead connecting it with the crystal electrode, but presumably this was of the order of 10 cm. (about 10 micro-microfarads). Assuming these dimensions and this capacity, the capacity of such a crystal plate, would be

$$C_c = \frac{Kbl}{4\pi d} = \frac{80 \times 1 \times 1}{4\pi \times 1/10} = 65 \pm \text{ cm.}$$

Hence the capacity of such a crystal plate would be more than six times the assumed capacity of the detecting apparatus; therefore the theoretical potential must be calculated on that basis.

$$q = \frac{DFI}{2d} = \frac{10^{-8} \times 8000 \pm \times 1}{2 \times 1/10} = 4/10 \text{ e. s. u.}$$

$$e = \frac{q}{C_c + C_e} = \frac{4/10}{65 + 10} = 4/750 \text{ e. s. u.} \\ = 1.6 \text{ volts.}$$

But Babcock obtained only 0.375 volt. So, under the conditions of his experiment, he found a value for the potential which was about 24% of the value indicated theoretically.

It will be useful to compute the elastic distortion produced by the varying force,

$$F = \frac{E \times b \times d \times \Delta l}{l} \quad (17)$$

$$\Delta l = \frac{Fl}{Ebd} = \frac{8000 \times 1}{4 \times 10^{11} \times 1 \times 1/10} = 2 \times 10^{-7} \text{ cm.} = 2\mu\mu$$

$\triangleright 2\mu\mu.$

Now, as Babcock himself points out, a deflection of one-half of a division of the scale could have been observed or photographed successfully. He obtained 15 scale-divisions deflection equivalent to $\frac{3}{8}$ of a volt for about 8000 dynes. Hence he could have determined successfully $\frac{1}{30}$ of this potential corresponding to $\frac{1}{30}$ of this force, a deflection of $\frac{1}{2}$ scale-division equivalent to about 12.5 millivolts due to a force of about 250 dynes.

For a force of 250 dynes, in Babcock's experiment,

$$\Delta l = 6 \times 10^{-9} \text{ cm.} = 0.06 \mu\mu.$$

Moreover, possibly because of both the excessive initial pressure and of neglect to balance the capacity of the crystal plate with that of the external insulated system, the potential obtained was not so high, either theoretically or practically, as the conditions in general would have permitted.

Consequently this experiment was repeated, using a string electrometer whose sensitiveness could be varied easily from 10 to 30 (and with some difficulty to 50) scale-divisions per volt, and Rochelle-salt crystal plates provided with two sets of electrodes connected in series, where $b = 1/2$, $d = 2/10$, $l = 1.2$, and $L = 2.4 \pm$ cm., so that the capacity of the crystal condenser equaled 10 cm., where the capacity of the electrometer string and insulated lead equaled $6 \pm \pm 10$ cm. In these experiments the lead wire was not shielded thoroughly, and leakage, presumably over the crystal surface, was rapid with static effects, but otherwise the electrical conditions were good. The mass used was 250 grams, so that the initial load was only a trifle too great for the best theoretical condition. Unfortunately, however, the lever and frame were poorly and hastily made and gave some trouble through

rocking of the lever on its pivotal bearing, an ordinary hinge. Nevertheless, as anticipated, greater sensitivity was obtained than that found by Babcock. The arrangement for applying to the crystal the varying pressure due to the radial acceleration of the swinging mass, was identical in principle with that employed by him. The leads from the crystal electrodes were led one to the string and the other to "earth" at the mid-point of a high resistance in an electrometer set-up shown by the following diagram, Figure 7.

Owing probably to the bad mechanical construction of the pressure-system, and doubtless to electrical leakage also, the results obtained were not wholly consistent, though, under all the circumstances, a majority of them were satisfactory. As expected, in all cases but one, a more sensitive response was obtained than Babcock got. The half-periodic time of the pendulum was from one-half to one-third second or less, different in different cases, so that the pressure effect had a frequency of four to six or more cycles per second. The force, in dynes, was computed by the approximate formula used by Babcock. The following table summarizes the findings.

I.	II.	III.	IV.	V.
4000+	20	20—	1—	4000—
4000—	5	4±	0.8±	5000±
4000—	10	6—12	0.6—1.2	3250—6700
4900	10	9—11	1±	4900
5200	15	22—23	1.5	3500

I. Force, computed in dynes.

II. Electrometer adjustment, scale-divisions per volt.

III. Deflections observed, corresponding scale-divisions.

IV. Corresponding potential, in volts.

V. Force equivalent, dynes per volt.

Rejecting observations which depart far from the normal majority, it is clear that in general it should be possible to obtain in practice a potential of about one volt for an applied force of about 5000 dynes, in the practical set-up; whereas for such crystal plates as those employed, on the basis of theory,

$$e = m \times 300 \times \pi d/bK \times F = 4.7 \text{ volts, for } D_{\min}.$$

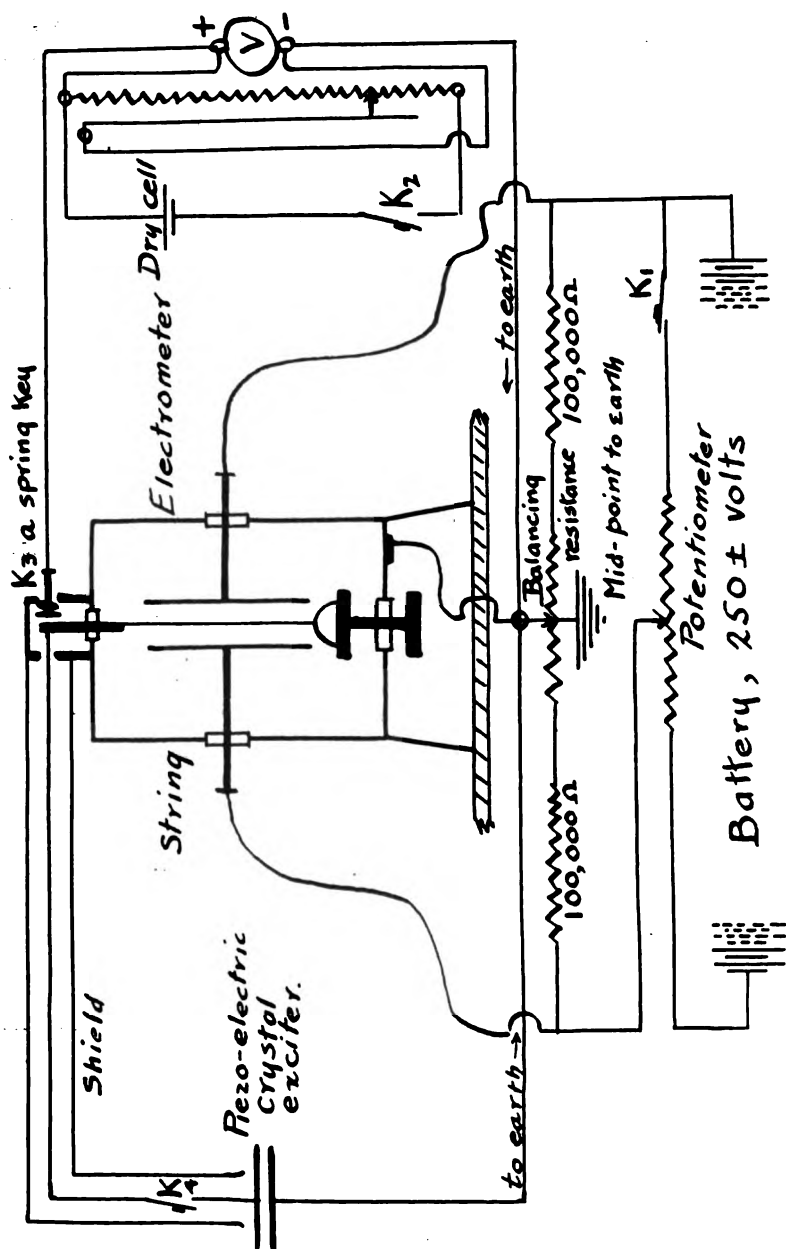


Fig. 7

Hence

$$e_{\text{observed}} = 21+ \% e_{\text{calculated}} ;$$

but taking D four times as great, which seems a more probable value for the constant,

$$e = 18\text{—volts}$$

and

$$e_{\text{observed}} = 5.6\% e_{\text{calculated}} .$$

In any case, on the basis of observation, when the electrometer is set at twenty scale-divisions per volt it is practicable to read $1/50$ of this, and so to detect a force of 100 dynes. And further, it is obviously safe to take Babcock's results and assume 400 dynes for a fiftieth-volt detectable by means of the electrometer.

On the basis of 5000 dynes applied on the end cross-section $1/2 \times 2/10 = 1/10$ sq. cm.

$$\Delta L = \frac{FL}{Eb d} = \frac{5000 \times 2.5}{4 \times 10^{11} \times 2/10 \times 1/2} = 3.1 \times 10^{-7} \text{ cm.} = 3.1\mu\mu ,$$

and on the basis of 100 dynes applied

$$\Delta L = 0.06\mu\mu ,$$

the theoretical change in length of the crystal plates.

The extraordinary sensitiveness thus demonstrated led to the trial of this method for detecting earth vibrations, and to the design of a ballistic accelerometer for use with the crystal plates. As expected this proved an unprecedentedly sensitive vibration detector. For, at minimum, $2m/10$ millivolts per dyne could be obtained.

The Piezo-electric Ballistic Accelerometer. As conceived originally by Galitzin, and modified in design for these experiments and seismic work, the piezo-electric ballistic accelerometer consists of three essential parts,

(1) a ballistic inertia-mass usually displaced slightly from its natural equilibrium position, as the pendulum-vertical, and then constrained in this position (or held up) by

(2) a nearly rigid piezo-electric crystal plate which is held by this initial pressure or tension between the inertia-mass and

(3) a buttress-member set into, or adequately attached to, rock or firm earth, or other vibrating body, so that it is constrained to follow or share as closely as possible the vibratory movements.

In the best practicable arrangement thought of, the buttress should take the form of a light, stiff member, such as a steel tube with walls of proper section, set firmly in rock and projecting but little above the immediate surface, preferably ending in a frustrum of a cone of suitable dimensions with its axis in the direction of applied force. (In the design I employed the buttress was a plate clamped to the heavy base of the ballistic pendulum, and all rested on the vibrating body. But this is not considered to be the best arrangement.)

The inertia-mass must be of considerable magnitude in order that the force derived from its reaction¹⁴ against small vibrations may attain detectable magnitudes. It should best terminate, where it is in contact with the crystal plate, in the frustrum of a cone, as in the case of the buttress. For the detection of horizontal components of acceleration it may well enough be suspended as a simple ballistic pendulum. Besides being heavy, it should consist of or be well backed with very stiff material, such as steel, where it is in contact with the crystal plate. Its best form, mass, and dimensions are not certainly known. Preferably, in theory¹⁵ the Young's modulus of the material of the buttress and of the inertia-mass should be the same, and of as high value as practicable above the modulus of the crystal material, for the purpose of the mechanism as a whole is to convert the reaction of the mass against vibration into elastic deformation of the crystal plate.

For, by means of this complete assembly, the to-and-fro movement of rock- or earth-particles due to the arrival and passage of pulses or wave-trains, propagated through the earth, is converted into force applied as variation in pressure upon the end cross-section $b \times d$ of the crystal plate.¹⁶

Therefore, since the mass is constrained to lean against the plate, to make an angle θ with the vertical, there is exerted upon the crystal plate, between the mass and the buttress, a steady force

$$f \text{ dynes} = M \text{ grams } g \sin \theta. \quad (18)$$

This initial force should be small, so as to provide, it is thought, an initial pressure of about 2000 grams per square centimeter—about 200 grams on the actual cross-sectional area used. For other reasons M

¹⁴ In such a set-up the phenomena of reflected wave motion must be considered in the strict analysis.

¹⁵ Some actual findings appear to throw doubt on this point, but the factors involved are so complex that it is difficult to reach a conclusion.

¹⁶ Except for reflection phenomena already referred to.

must be large. Hence ϑ and $\sin\vartheta$ must be small, and in fact practically negligible.

$$\sin\vartheta = \vartheta = 0.$$

When the earth, or a platform, vibrates through an amplitude, a , an additional force is generated, given strictly by the formula

$$f' = \pm M a'' \cos\vartheta. \quad (19)$$

Therefore

$$f = M g \sin\vartheta \pm M a'' \cos\vartheta$$

$$F = f - f_0 = M a'' \cos\vartheta = M \frac{d^2 a}{dt^2} \cos\vartheta$$

$$F = M a \cos\vartheta \quad (20)$$

for any arbitrary law of motion, $a = f(t)$, but we may take the vibration to be sensibly harmonic motion, so we may write

$$a_{\text{cm/sec}^2} = \frac{4\pi^2}{T^2} x_{\text{cm}}. \quad (21)$$

$$a = 2\pi^2 n^2 a \quad (22)$$

whence

$$\begin{aligned} F &= 2 M \pi^2 n^2 a \cos\vartheta \\ &= 2 M \pi^2 n^2 a [\cos\vartheta \doteq 1 \text{ as } \vartheta \doteq 0] \end{aligned}$$

Strictly, of course, the term, $\cos\vartheta$, should be retained, and a term should be included also for the effect of vertical acceleration since ϑ is not strictly zero; but for all practical purposes this may be neglected, despite the fact that in some other aspects extremely small magnitudes enter the analysis intrinsically. This is all the more true since, in accordance with a common practice in physical approximation, it will be assumed that the to-and-fro translation of the center of the ballistic inertia-mass is only one-half that of the amplitude of vibration of the earth-particle or platform. As will be seen, this assumption ought completely to compensate for all elastic and viscous losses in the system, and leave a safe margin for practical computation and deduction.

Hence, for the value of the effective force in dynes

$$F = M \pi^2 n^2 a \quad (23)$$

may be written safely for the maximum, or peak, value of the harmonically varying force.

At this point it must be noted that, whatever the value of F , it cannot act through a distance greater than a , or in reality quite so great as a , since inevitably there would be viscous and elastic losses.

Therefore, even if the crystal were of negligible rigidity it could not be compressed more than a no matter how great the force might be. But, as will presently be clear, with any practicable crystal-plate member and any practicable mass, the force generated by vibration of very small amplitude with frequencies between one and 100 cycles per second is not sufficient to produce a change of length of the crystal plate ΔL as large as $a/2$; that is, a , though itself only a very small magnitude, must yet be a considerably larger quantity than ΔL in order to bring into play a sufficient force to make $\Delta L/L$ great enough to set free a detectable piezo-electric charge. For

$$\frac{\Delta L}{a} = \frac{FL}{Ebd} \times \frac{M\pi^2 n^2}{F} = n^2 L \times \frac{\pi^2 M}{Ebd}. \quad (24)$$

In the work immediately under discussion M was made about 35,000 grams, $b = 1/2$ and $d = 1/4$ centimeters, and n was found to lie between 10 and 100 cycles per second, with many values in the neighborhood of 50. Hence

$$\frac{\Delta L}{a} = \frac{2}{100} L \text{ or } a = 50 \frac{\Delta L}{L},$$

a suitable assembly for values of L up to about 25 centimeters.

Further, in dealing with extremely small magnitudes in ΔL and a , consideration of the elastic deformations which are produced cannot be neglected wholly, even though, by taking $F = Mn^2\pi^2 a$, liberal allowance has been made for them.

The buttress member, which is constrained to follow the vibratory motion in general will have different elastic moduluses from those of the vibrating body to which it is affixed. Hence, the excursions of its particles will not be identical in amplitude. Through reflection, refraction and lost motion in general, they will be less, so that

$$a' = a - \varepsilon.$$

Where the buttress and crystal plate are in contact, as the vibration proceeds the buttress will be variably indented by the crystal plate, and the crystal plate will be subjected to variable thrust-impact from the buttress. Similar variable indentation and thrust-impact will occur where the crystal plate touches the ballistic mass. Of course, in a static configuration, since action and reaction are equal and opposite, the compression of the crystal member would not be affected by this: but in a rapid cyclic dynamic configuration this cannot be assumed. The values of ΔL under such circumstances requires experimental

investigation. However, it is evident that, on account of the bending of the buttress member and the changes in length of the crystal plate, the amplitude of the motion of the center of inertia of the ballistic mass thus produced must always be smaller than the amplitude of the vibration.

Under the conditions specified the crystal plate will be held in an initial state of strain and therefore in a given electrical status when there is no vibration. This electrical status may be defined as null. Under the added force resulting from vibration, change in strain will be produced, first in one direction and then in the other, and corresponding electric charges will be set free, first of one sign and then of the other. From one extreme of amplitude to the other the charge with a given sign will increase, and then in reverse, so that maxima of quantity and potential are reached at each extreme of amplitude, their peak value depending upon the force generated.

To detect or register the vibratory motion these charges are led as potential to the string of a string electrometer or to the grid of an audion assembly, or as current through a string galvanometer. When the vibration approximates to simple harmonic motion approximate sine curves are obtained which obey the law

$$F = \bar{F} \cos \omega t \quad \text{where } \bar{F} = M\pi^2 n^2 a.$$

So much for the description and theoretical considerations bearing upon the method employed. Galitzin has given the simple dynamical theory of the action.

Much experimental work was done in development, but only a little field testing with the most advanced assembly of apparatus.

In early laboratory experiments, using a light inertia-mass, suspended and applied as in the Babcock experiment, with a string electrometer adjusted to deflect 25 scale-divisions per volt, exceedingly minute vibratory disturbances were definitely and consistently detected. Very light taps made on a table or on the walls in a remote part of a laboratory room of considerable size, taps barely perceptible to the person making them, were always definitely detectable.

In the field, using make-shift ballistic pendulums put together in very crude ways, footsteps on turf growing on a well-consolidated river gravel stratum were readily detected visually with the string electrometer set-up at all distances from the crystal detector up to about sixty yards. With this set-up, too, vibrations were detected

visually which were due to the starting up of trains at a station across the Potomac river at a place where it is nearly two miles broad. This, though strongly indicated, was not proved directly, but evidence constituting proof of it was obtained from later work.

USE WITH THE "AUDION," AS AN AMPLIFIER, COMBINED WITH AN
OSCILLOGRAPHIC GALVANOMETER

With the string electrometer about $\frac{1}{50}$ of a volt was the lowest rapidly alternating potential which could be read easily by visual or photographic observation. (Perhaps as little as $\frac{1}{250}$ of a volt could have been detected barely, with some uncertainty.) This could have been improved upon slightly, but not in sufficient degree. But by use of the "audion" combined with a special oscillographic galvanometer it was possible to register easily and surely potentials considerably lower than this, and, therefore, feebler disturbances. And in this direction there is still abundant opportunity for progress toward more sensitive, and what is still more important, more reliable assemblies.

The most satisfactory of the audion-oscillograph assemblies which became available in this investigation was the outcome of many experimental set-ups, each in some respect better than those tried previously, but all this was work of pioneering which had not proceeded very far before it was interrupted by the termination of this investigation. Much further improvement in this part of the apparatus is undoubtedly possible.

In the best set-up the varying potential from one electrode of the crystal plate was led directly to the grid of the first lamp of a three-stage, audion amplifier, and the other electrode of the crystal plate was connected to earth. Schematically the construction of the amplifier, and its connections, are shown in the diagram, Figure 8. The secondary of the output transformer of the amplifier was connected with the oscillographic galvanometer. Thus there are three essentially different parts in this assembly of apparatus, the sensitive piezo-electric exciter, the amplifier, and the recording galvanometer.

The piezo-electric member, and its response to acceleration, have been discussed at length.

Detailed discussion of the theory of action of the amplifier cannot be undertaken here. Briefly, it is a device which, by drawing upon external sources of electric current from batteries, can furnish through its output transformer, a current, or variation in potential, similar or

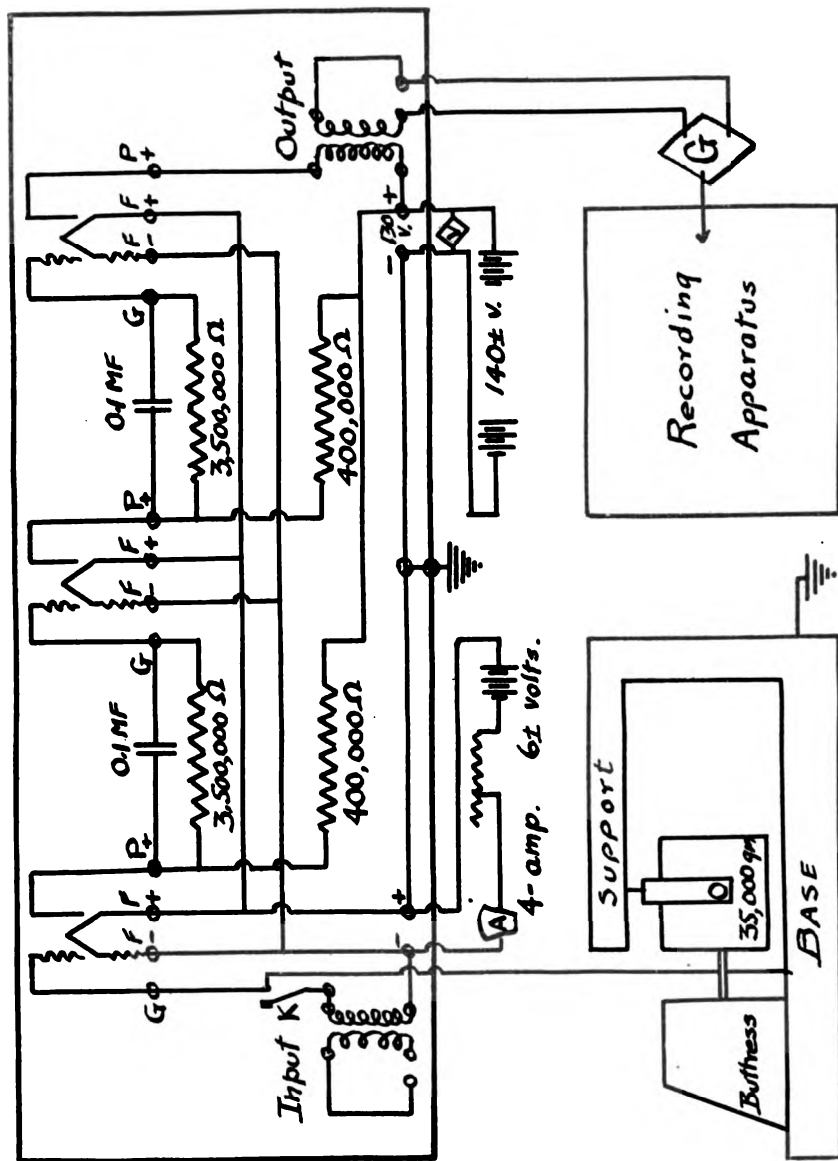


Fig. 8

identical, in characteristics with the current, or variation in potential, impressed on the grid—in this case by the crystal—but many times greater. The grid has been likened aptly to a throttle controlling with the expenditure of very little power the power of a great engine.

For such use as in this work the amplifier must be designed to minimize distortion at the output end of the variation in current or potential impressed upon the grid, and to avoid oscillation, a behavior of the audion cultivated for use in some work but fatal in this. To a considerable extent the amplifier used was successful in these respects, but much further improvement should be possible.

The oscillographic galvanometer used was a moving coil type of very small mass in the moving part, arranged to write mechanically with a light metal stylus on a moving tape of smoked paper. Of those available the galvanometer elements found best adapted for use with the secondary of the output transformer of the amplifier were wound with resistances of forty ohms. These elements, when used directly with the microphone transformers for which they were designed especially, are most efficient with an alternating current of twelve cycles per second. Thus used they write a deflection of about one millimeter for a current of one milliamper. (Owing to variable friction at the point of the scribe, in actual use, no precise "figure of merit" or calibration constant can be given.) But used with the output transformer of the amplifier these galvanometer elements were found most efficient when the current-frequency was in the neighborhood of twenty-five cycles. However, the difference in amplitude for a given current strength was slight over a considerable range of frequency. And a frequency of twenty-five cycles per second is inside the range of the vibration-frequencies under observation in this investigation, though twenty-five is only about one-half the value of the frequencies of vibration probably most often experienced. Therefore, though it was wanting in refinement in many ways, in this fundamental respect this part of the apparatus was fairly well adapted for the work in hand. But, when used with the amplifier, the current efficiency of the galvanometer, its approximate figure of merit, was never determined.

Thus, with the train of apparatus described, there was obtained a vibration-recorder of very great sensitivity, having, too, an exceedingly high factor of magnification which was not determined precisely but which was approximated as follows:



Fig. 10



Fig. 11

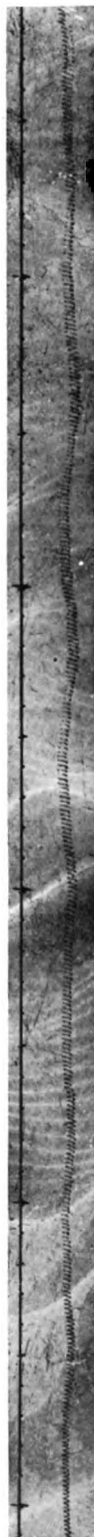


Fig. 12



Fig. 13

- 1 Arrival of earth disturbance.
- 2 Arrival of extraneous disturbance.
- 3 Arrival of sound of explosion.

3

2

1

By an arrangement of three potentiometers in series, as shown in the diagram, Figure 9, direct and alternating currents, each of 110 volts potential, were so controlled that for the total length of the one-meter wire of the third potentiometer there existed with the direct current a potential of ten millivolts—whence it is assumed that the peak value of the alternating current potential for this length was $10\sqrt{2}$ millivolts. Then from this potentiometer wire alternating current of very low potential was tapped off to the grid, and to the filament as “earth,” of the amplifier. (With this a plate voltage of 142 volts was used, and through the filament a heating current of 3.9 amperes at 6 volts was passed.) The amplitude of the sine wave then written by the recording galvanometer varied with the potential impressed on the grid, and the system wrote a faithful sine curve with the frequency of the alternating current employed, which in the course of the experiment was varied from 12.5 to 180 cycles; but for the calibration test the preferred value of 25 cycles was used.

With the arrangement shown and a frequency of twenty-five cycles, it was found that the total amplitude of the written sine-curve (for the given pressure of the writing scribe) was one millimeter when the reduced value of the impressed alternating potential was seven millivolts (see Fig. 10). This was when alternating current tapped off from a dynamo-electric machine was employed. The probable assumption has to be made here that alternating potential from the piezo-electric crystal condensers produce like effects quantitatively to a sufficient approximation. (This is altogether probable, but differences in capacity relations may enter and make it uncertain in a strict quantitative sense.) On this basis a potential of seven millivolts impressed on the grid from the electrode of the crystal produces deflections of one millimeter.

The amplifier itself, calibrated by means of the triple potentiometer and an alternating current of 25 cycles, had under these conditions an amplification ratio of about $180\times$. Presumably this was true with the potential from the crystal condenser also.

With the string electrometer adjusted to deflect 25 scale-divisions per volt one scale-division (one visually apparent millimeter) corresponded to 40 millivolts. Therefore this amplifier-oscillograph, besides giving a written record by a comparatively inexpensive mechanical method of registration, was about six times more sensitive than the string electrometer. And by using with it an optical method of regis-

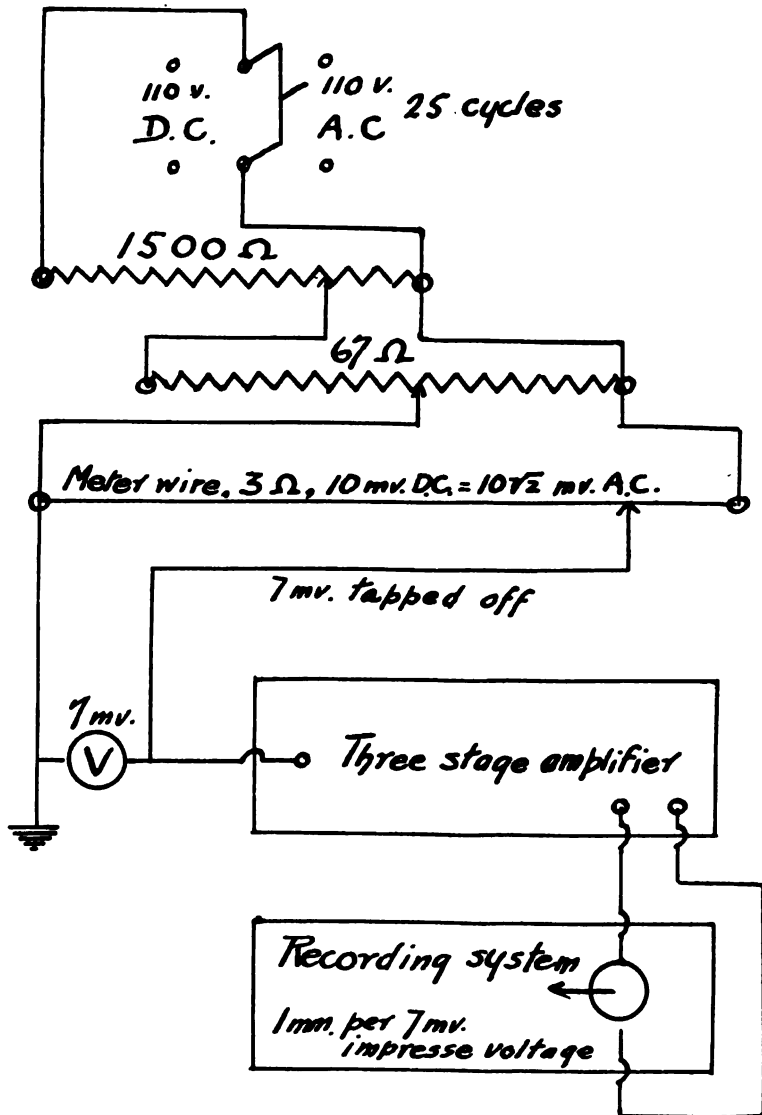


Fig. 9

tration (the only method which could be used with a string electrometer) the magnification could have been increased further very greatly indeed.

MAGNIFICATION OF THE EARTH VIBRATION

Of the magnification of the amplitude of vibration in the earth only a very crude approximation is possible: (*a*) because of the several assumptions it has been necessary to make in connection with the crystal member of the apparatus, and (*b*) because the magnification due to the amplifier-oscillograph is only approximately determined. But the least value of this magnification is very great, surpassing most previous maximal values, and for vibrations of high frequency, above 100 cycles, it becomes very great indeed.

To go back a little, it was found that when a short crystal plate equipped with a single pair of electrodes was used—the least favorable arrangement—a force no greater than 200 dynes would set up an accurately measurable potential as great as 10 millivolts, even when the conditions of capacity balance were ill-adjusted; while with better balance of electrical capacities and longer crystal plates having two or more sets of electrodes connected in series a force no greater than fifty dynes—and very probably forces less than this—would set up a potential as great as ten millivolts as found quite accurately with the string electrometer. This potential, be it noted, is slightly greater than the seven millivolts required to register a deflection of one millimeter by means of the amplifier-oscillograph assembly. Therefore, once more, exaggeration is avoided if 50 and 200 dynes are taken as limits for the range of the force required to produce a registered amplitude of one millimeter with the train of apparatus described. But it should be noted that fifty dynes is probably closer to the truth than 200, and even that it is very probably larger than the actual value required.

The vibrations, dealt with in the investigation under report, had frequencies lying inside the range between 10 and 100 so far as is known, with values near 50 far more common than others.

Taking the values just cited as limits and norms, approximate values for the magnification of the amplitude of vibration of the earth particle are found by substitution in the formula,

$$a = \frac{F}{n^2 \pi^2 M} \text{cm.} = \frac{10 F}{n^2 \pi^2 M} \text{mm.}$$

In round numbers these values are shown in the following table:

F (dynes)	n (cycles)	a (mm.)	Magnification
200	10	1/17,500	17,000+
200	50	1/437,500	437,000+
200	100	1/1,750,000	1,700,000+
50	10	1/70,000	70,000±
50	50	1/1,750,000	1,700,000+
50	100	1/7,000,000	7,000,000±

Hence, having made liberal discounts and allowances intended to avoid exaggeration throughout this work, since the conditions of experimentation did not permit the attainment of precision, there comes out as the most probable value for the magnification of the amplitude of the vibrating earth particle a value of $70,000 \pm \times$ when the frequency of vibration is 10 and of $1,700,000 + \times$ when the frequency is 50.

The extreme limits computed above are $17,000 + \times$ and $7,000,000 \pm \times$. There is little possibility that the smallest value is not too small. But, on the other hand, there is much probability that the greatest value is not large enough (when $n = 100$), even though this is somewhat staggering to the imagination of seismologists. And with optical registration this, even, can be increased greatly.

Previous studies of minute, rapid earth vibrations have been made by many, especially by Grunmach¹⁷ and by Mintrop¹⁸, both of whom worked under conditions permitting better control of experimentation.

Mintrop used a steady mass cradled in a complex way to measure a horizontal component of amplitude by a combined mechanical and optical photographic method of registration by which he could obtain a magnification of $16,000 \times$ on the photographic film. In some secondary way, of which no clear description has been seen, he obtained further magnification up to about $50,000 \times$. His method does not depend upon frequency (except in so far as resonance enters), but only upon amplitude, and though probably not strictly precise, it makes

¹⁷ Grunmach, Leo, "Experimentaluntersuchung zur Messung von Erderschütterungen," Berlin, Leonhard Simion.

¹⁸ Mintrop, L., "Ueber die Ausbreitung der von der Massendrucke einer Grogasmaschine erzeugten Bodenschwingungen" (Dissertation), Göttingen, 1911. Cf. also *Engineering*, 93, 7-10, 1912.

a close approach to precision. But his magnification factors are small in comparison with those obtained in this work with frequencies in excess of ten cycles per second.

Grunmach employed a simple horizontal pendulum with electromagnetic detection and registration, by the photography of the string of an Einthoven galvanometer. His work appears to have been done with great thoroughness. It is the most precise measurement of small vibratory motion so far made. Like the piezo-electric method, his depends upon frequency for sensitiveness and magnification. With frequencies of 200 cycles per second he detected vibration amplitudes as small as 8 to 16 ten-millionths of a centimeter. This magnification—with frequencies of 200 cycles per second—is of the same order as that obtained in the present work, with frequencies of 50 cycles per second. Grunmach could only detect much greater minimum amplitudes of vibration. Therefore his method does not rival in sensitiveness or magnification the piezo-electric accelerograph. Only in accuracy does it exceed it.

During the development of the amplifier-oscillograph assembly, before it had been made as sensitive and as reliable as later, footsteps on turf growing on moderately well consolidated river gravels were registered with amplitudes of about one centimeter where the nearest steps were more than forty-five feet distant from the accelerometer, as shown in Figure 11. At the time of this test, the "audion" member was in poor adjustment, and did not respond to charges impressed upon the grid until these rose to a considerably higher potential than is ordinarily required to modulate the thermionic current. In consequence of this, on this particular record the responses to disturbance do not grade in amplitude as they usually did, but begin and cease abruptly with considerable values of amplitude. On the same day, with the string electrometer, responses to footfalls could be perceived visually at all distances up to about sixty yards.

At about the same stage in the development of the apparatus, on three occasions a written record was obtained of vibrations caused by the starting of a train on the opposite side of the Potomac River at a place where it is nearly two miles wide. The train could be heard and seen getting under way while the vibrations were being registered. The record, Figure 12, shows a dominant long, flat, sine-wave motion considered due to the relatively slow pounding effect of the driving wheels under the back-and-forth reciprocating thrusts of the levers

before the engine has begun to roll freely, and, superposed upon this, short, quickly reversed motions believed to be caused by the shivering of the rails under the impulses from the driving wheels. (However, these shorter vibrations may be complicated with "oscillation" effects which had not at this time been eliminated satisfactorily from the amplifier.) As the train picked up motion so that the driving wheels rolled more freely and pounded less, all these vibratory motions diminished and gradually died away.

While this interpretation of such records, obtained on three occasions, may not be considered absolutely sure, it is most probably sound, and these effects are altogether in proportion to other proved effects.

In Figure 13 the record shows wave-motion transmitted through a light, loosely compacted stratum of sand from an origin distant from the accelerometer more than 2,900 and less than 3,100 feet. This earth disturbance was generated by explosion, the sound of which could be heard plainly. Also the arrival of the sound was itself registered both by the accelerometer and by auxiliary apparatus. The arrival of the vibration through the sand stratum preceded the arrival of the sound through the air by an interval of 2.6 to 2.7 seconds. The sound, proceeding at the rate of $1,100 \pm$ feet per second, must have occupied between 2.6 and 2.8 seconds in reaching the accelerometer. Consequently, the vibration in the earth occupied less than two-tenths and more than one-tenth of a second in traversing more than 2,900, and less than 3,100, feet of loosely compacted sand, a rate of transmission not so slow as 14,500 feet per second, and, with much probability, approximately as fast as that of the first-phase waves of earthquakes, i. e., approximately seven kilometers per second.

This experiment was repeated successfully several times. However, owing to deficiencies in one or another part of the complicated mechanism of the accelerograph as a whole, and to numerous adverse conditions in the field which could not be brought wholly under control, records of earth-waves were not obtained invariably, under what appeared to be like conditions of causation, at the origin. At this stage of the investigation the work was brought to a close.

In the present state of knowledge, the procedure, necessarily followed here, has not yielded precise results. But there appears no reasonable doubt that with an improved oscillographic galvanometer

(probably utilizing optical registration), an improved amplifier, with the assembly properly shielded electrically, together with the necessary calibration curves, this can be made a precise method for measuring the acceleration of vibratory motion, probably with quartz which, though less sensitive, is far less subject to extraneous factors than Rochelle-salt. This will then be far the most sensitive method known for measuring the force of vibration.

VARIABLE VELOCITY OF *L* WAVES

By ERNEST A. HODGSON

During the routine work of digesting the data given by various stations into the form used for locating epicenters, the record for May 9, 1917, at 16 hrs. $\pm$, G. M. T., was examined in its turn. Discarding those readings, which, by reason of the extreme error in the *O* or Δ yielded by them, were plainly in error the following remained:

Stations.	<i>P</i>			Δ	<i>O</i>			Measured Δ
	H.	M.	S.	KM.	H.	M.	S.	KM.
Ottawa	16	14	25	8380	16	02	45	13000
Barcelona	16	14	32	8840	16	02	28	13100
Algiers	16	14	52	9000	16	02	39	13400
Paris	16	14	04	8020	16	02	42	12400
Honolulu	16	05	24	7020	15	54	55	6600
Manila	16	00	00	2510	15	54	52	2300
Berkeley	16	07	30	9620	15	54	47	10000
Zi-ka-wei	16	00	53	3050	15	54	50	3300

An examination of the *O*'s showed that they fell into two groups, one about 16^h 02^m 38^s and the other at about 15^h 54^m 51^s. The first conclusion was that there were two earthquakes, or that the epicenter was an elongated fault line. This hypothesis was soon found to be untenable owing to the distribution of the stations. Then it was found that Manila quoted a dispatch from Guam, Marianne Islands, showing that the earthquake occurred near there. The last four stations whose average for *O* was 15^h 54^m 51^s, define an epicenter at approximately $\phi = 8^\circ \text{ N.}$, $\lambda = 140^\circ.5 \text{ E.}$, a little to the south of the Marianne Islands. This was taken as the probable epicenter, and the value, 15^h 54^m 51^s, was taken as the approximate value for *O*. The Δ 's for the various stations were then measured on a 30" globe and the measures set down in the last column of the above table.

Taking these values for Δ , the *P* for the first four stations should come at about 16^h 09^m to 16^h 10^m and the *PR*₁ at about 16^h 14^m+. Evidently these stations have recorded as *P*, a phase which is really *PR*₁. This is a common difficulty in reading the records of distant earthquakes. It is usually prevented by the check afforded by the appearance of the *L* waves.

Our original record was examined to see whether this check had been applied, and if so, why it had failed in this particular case. Knowing O and the Δ for Ottawa, the time of arrival of the L waves was computed as 16^h 52^m ca. The report originally made in our bulletin of this record gave the time of arrival as 16^h 39^m. Examination showed that they were doubtful at that time but were plainly visible at 16^h 45^m, some seven minutes earlier than was to be expected. This led to a further investigation into the L waves as recorded for this one disturbance.

The other stations reported L as well. The values of Δ being known, the values for V_L were computed. These are given in the following table. Column 1 indicates the measured Δ , the second column shows the reported time of arrival of the L waves at the station, and the third contains the computed velocity of the propagation of the L waves from the epicenter to the given station. The fourth column of the table gives the results for the computations of V_L , and it will be noted at once that these are extremely varied. From the records of the Messina earthquake of December, 1918, as registered at Pulkowa, Galitzin found that the L waves passed around the earth with an average velocity of 212 km. a minute. This was not far from the

Stations.	Measured Δ	L			V_L	% Water
	KM.	H.	M.	S.	KM.	
Ottawa	13000	16	44.5		262	58
Barcelona	13100	16	50	15	236	24
Algiers	13400	16	50		243	31
Paris	12400	16	46		243	37
Honolulu	6600	16	21	18	250	80
Manila	2300	16	04	06	250	80
Berkeley	10000	16	30	09	283	100
Zi-ka-wei	3300	16	07	45	263	90

value required for Rayleigh waves, viz, 221 km. a minute. But many cases have since been found varying considerably from these values, and in 1916 Dr. Klotz, in preparing his collection of seismological tables, averaged the results of 234 earthquakes, registered at Pulkowa and Ottawa and took the mean value (228 km. a minute) as the velocity of the L waves. In a later publication,* Dr. Klotz made a re-determination of this value and arrived at a velocity of 230 km. a minute. This resulted from the use of 347 records, distributed among thirty stations.

On endeavoring to find an explanation for the differences in ve-

* *Bulletin of the Seismological Society of America*, 7, 67.

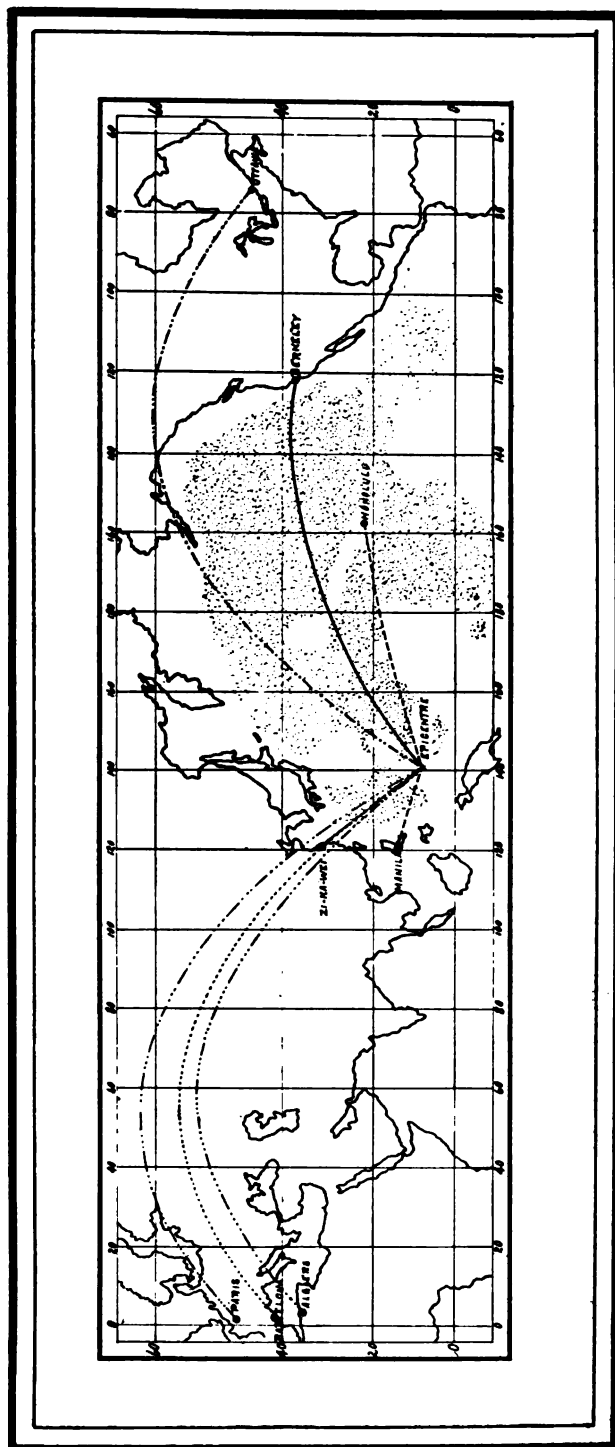


Fig. 1. Paths of the L waves.

locity as indicated in the table above, it was noted that the stations yielding a high value received the *L* waves after they had traversed a path through the deep portions of the Pacific Ocean. The accompanying map shows these paths of the *L* waves assuming that they traveled by the shortest path from epicenter to station. The percentage of the path which is deep water was measured and the values set down in the fifth column. The dotted areas of the Pacific are those parts which are over 15,000 feet deep according to the "Century Atlas of the World." They are dotted in approximately and serve to show that while the path to Berkeley is 100 per cent deep water, that to Zi-ka-wei is only, say, 90 per cent deep water, owing to the fact that much of the path lies in the comparatively shallow water of the archipelago. Similarly the paths to Honolulu and to Manila are taken as 80 per cent deep water, as much of their length lies in shallow water. The paths to the other stations are estimated according to the actual percentage of the water path involved.

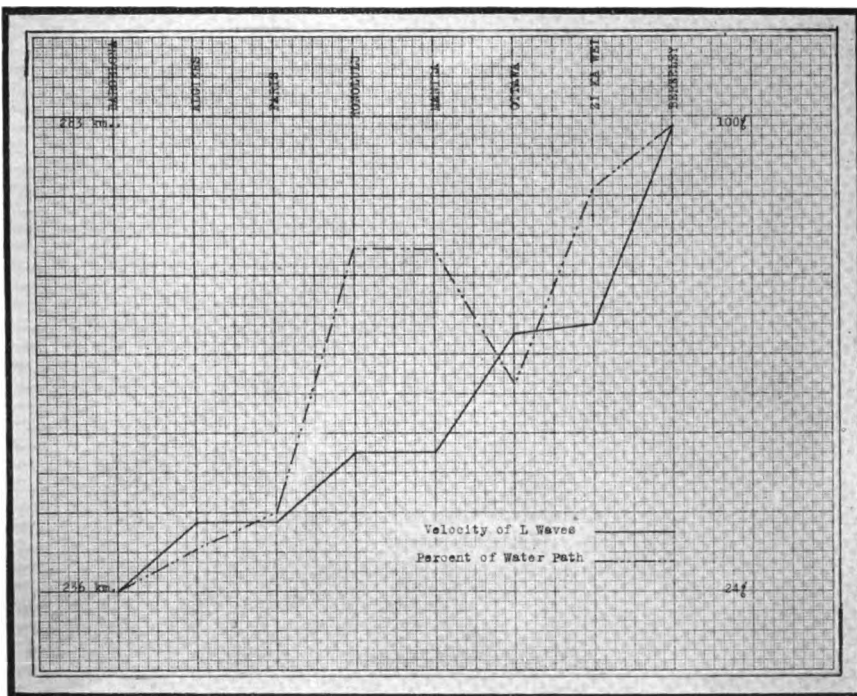


Fig. 2. Comparison Graphs. Velocity of *L* Waves vs. Percent of of Water Path.

As will be seen from a comparison of columns four and five of the second table, there is a marked parallelism between the percentage of the water path to the whole and the velocity of the L waves. It so happens that this earthquake, although particularly well situated for this investigation, was not very well marked in the record, and the study in this case can go no farther along lines utilizing numerically the values obtained. They serve to show beyond any doubt, however, that there is a pronounced effect upon the velocity of the L waves, due to the nature of the path traversed. The curves drawn from the data in columns four and five above bring out this correlation graphically.

As the work of locating epicenters proceeds, records will be kept in an effort to secure further data bearing upon this matter. It is to be expected that further investigation will reveal other earthquakes of a more decisive character which will enable the values obtained to be subjected to a quantitative analysis. The record above leaves little doubt in the mind of the writer that the effect will be found to persist.

DOMINION OBSERVATORY, OTTAWA, CANADA
September 10, 1920.

THE LOS ANGELES EARTHQUAKES OF JULY, 1920

By STEPHEN TABER

INTRODUCTION

During the last few months Southern California has been subjected to a series of earthquakes, more than one hundred shocks having been recorded during the period from February 1 to September 30, 1920. With a few exceptions they have been of low intensity, and most of them should possibly be classed as aftershocks of the principal disturbances. They have originated, however, in several different localities.

The earthquake at 8:10 a. m.¹ on February 22d was the first that resulted in damage to property. The origin was probably not far from the Soldiers' Home near Sawtelle, and the maximum epicentral intensity was about VI in the Rossi-Forrel scale. The strongest shock of the series, which had an epicentral intensity of over VIII, occurred on June 21st. It originated immediately west of Inglewood. This earthquake was described in a previous paper.²

The next earthquakes causing damage occurred on July 16th, and they had their origin in the northern part of the city of Los Angeles. The writer went immediately to Los Angeles, arriving the following morning, and spent four days there collecting information and investigating the effects of the shocks.³

Following the earthquakes of July 16th several shocks were felt during the months of July and August. The strongest of these aftershocks which occurred on July 26th, was investigated for the Seismological Society by Mr. F. Rolfe.

A number of earthquakes were felt in Los Angeles during the early summer; but, of those reported prior to July 16th, only the one that occurred at 9:25 a. m. on July 9th is believed to have had its origin

¹ Pacific Standard Time (one hundred and twentieth meridian), which is eight hours later than Greenwich time, is used throughout this paper.

² Stephen Taber, "The Inglewood Earthquake in Southern California, June 21, 1920," *Bulletin of the Seismological Society of America*, 10, 129-145, September, 1920.

³ This investigation was financed from funds allotted to the Seismological Society of America by the American Association for the Advancement of Science.

within the city. This shock was reported to the office of the U. S. Weather Bureau by Mr. P. Hansen as having an intensity of III-IV.⁴ It was not reported from any place outside of the city. The earthquakes of July 16th, although of lower epicentral intensity than the Inglewood earthquake, affected Los Angeles more than any of the other shocks in the recent series; in fact, it has been many years since Los Angeles was subjected to earthquakes of as high an intensity.

DESCRIPTION OF THE EARTHQUAKES ON JULY 16TH

The first of the earthquakes in Los Angeles on July 16th occurred at 10:08 a. m. It had an intensity of VI R.-F. in the business district; a little plaster fell in a few houses, bricks were thrown from several chimneys, and a small number of bottles were overthrown in drug-stores. People rushed from many of the buildings and a very few persons were slightly injured. The best estimates indicate that the duration of the earthquake was about four or five seconds. The shock was described by several persons as being similar to a blast or explosion under the ground. There was a sharp up-and-down vibration which broke a few windows and light globes but did not set chandeliers swaying.

Mr. F. A. Ralph felt a light shock at 12:19 p. m. and another three minutes later, but these were not generally felt. Mr. Ralph was sitting quietly in his office on the eleventh floor of a steel-frame building and was, therefore, favorably located for the purpose of observing light earthquakes.

The next shock occurred at 1:27 p. m., and it was followed by another at 1:30 p. m., both of them having an intensity of about VI R.-F. in the business section of Los Angeles, although the last shock was appreciably the stronger of the two. The duration of each of these shocks was estimated to be not more than three or four seconds. They were described as having a sharp up-and-down vibration similar to the morning shock; and, especially in the northern portion of the city, they are said to have resembled explosions.

At 4:49 p. m. a light shock was felt in the northern part of Los Angeles, where the intensity was about III, but it does not seem to have been noticed in other sections of the city. Mr. F. Rolfe, who was in a house at the corner of Union Avenue and Council Street, states that the shock felt as though the ground had been struck by a heavy body. The glass doors of a bookcase rattled and were opened by the jar.

⁴ *Monthly Weather Review*, 48, 434, July, 1920.

The last shock on July 16th was recorded at 6:13 p. m. It had an intensity of IV in the northern part of Los Angeles. Mr. Rolfe was walking on Belmont Avenue between Council and Temple Streets when the shock occurred. He felt a pronounced jar as though a heavy weight had suddenly struck the earth, and noticed that electric wires and similar objects did not oscillate. This shock was generally felt throughout the northern and central portion of Los Angeles, but does not seem to have been noticed in Pasadena only eight or nine miles away.

All of the earthquakes felt in Los Angeles on July 16th were of short duration, and all were characterized by sharp vertical vibrations. Many persons in the city commented on the marked difference between these shocks and the earthquake of June 21st, which, in Los Angeles, had a slower oscillatory motion that set the chandeliers swaying. Observers in Los Angeles state that the shocks on July 16th did not cause chandeliers, telephone wires and other suspended objects to oscillate appreciably. The testimony of observers in regard to the character of the motion is supported by the effect of the shocks on street lamps and other objects. Many lamp globes were broken. These glass globes rested on top of cast-iron columns and were held in place by small set-screws; therefore they could not have been injured by a relatively slow oscillating motion but only by a sharp blow or jar. Broken globes were noticed especially in West Lake Park, Pershing Square, and on Pico Street between Figueroa and Main Streets. Window panes were shattered in some buildings, and a few plate-glass windows in store fronts were cracked where the glass had been set rigidly in the frames.

Three of the shocks were strong enough to cause damage to property, but the total loss was small in view of the fact that the earthquakes originated within the limits of a city having a population of over half a million. Only a very small percentage of the buildings were in any way injured. The commonest damage consisted in the fall of a little plaster; a few bricks fell from ornamental cornices and from chimney tops; ornamental pediments were shaken from several buildings and some old, weak walls were cracked.

The walls of the old County Courthouse were slightly cracked in several places, but the cracks were formed only in the mortar and did not extend across any of the sandstone blocks. A few large ornamental stones fell from the roof to the pavement. These stones were finials (two and one-half feet high and one foot in diameter at the base) which

capped abutments flanking the dormers. Inside the building plaster fell from ceilings and walls in some of the rooms.

No deaths resulted from the earthquakes, but several persons were treated at the hospitals for minor injuries caused by falling brick and stone or broken window glass. At the time of the afternoon shocks a man is said to have had his leg fractured by a falling brick near the corner of Fifth Street and Broadway. People rushed from the buildings after each shock; many women fainted and some had hysteria. Business was practically at a standstill after the afternoon shocks, and many stores and offices closed for the day.

The principal shocks were recorded on volt meters in Los Angeles and vicinity, but the minor shocks could not be distinguished because of fluctuations in voltage.

LOCATION OF THE EPICENTERS AND DISTRIBUTION OF INTENSITIES

The approximate determination of the epicenters was an easy problem, for the intensity of the shocks died out very rapidly in passing away from the origin through the relatively unconsolidated rocks of the district. All of the shocks originated in the northern part of the city of Los Angeles and within an area that probably does not exceed four or five square miles.

The precise determination of the epicenter of each shock is difficult; the three principal shocks were of nearly the same intensity and comparatively few observers distinguished carefully between the effects produced by each.

In the business section nearly everyone agreed that the shock at 10:08 a. m. had the highest intensity, but in the residential district north of Sunset Boulevard the two shocks, occurring at about 1:30 p. m. were generally considered the strongest. Most observers in Los Angeles were unable to distinguish any difference in the intensities of the two afternoon shocks, but some thought that the second was the stronger. At a distance from the origin where the intensity of the shocks was low, the one at 1:27 p. m. was weaker than the one at 1:30 p. m.

In locating the epicenters of the three principal shocks, the best evidence as to the relative intensity at different places was obtained by comparing the effects of the earthquakes on bottles and boxes in drug stores. Drug stores are to be found at intervals of about one-half mile throughout the area most strongly affected by the shocks.

These stores are all on the ground floor, and they all have many bottles of different shapes and sizes similarly arranged on shelves.

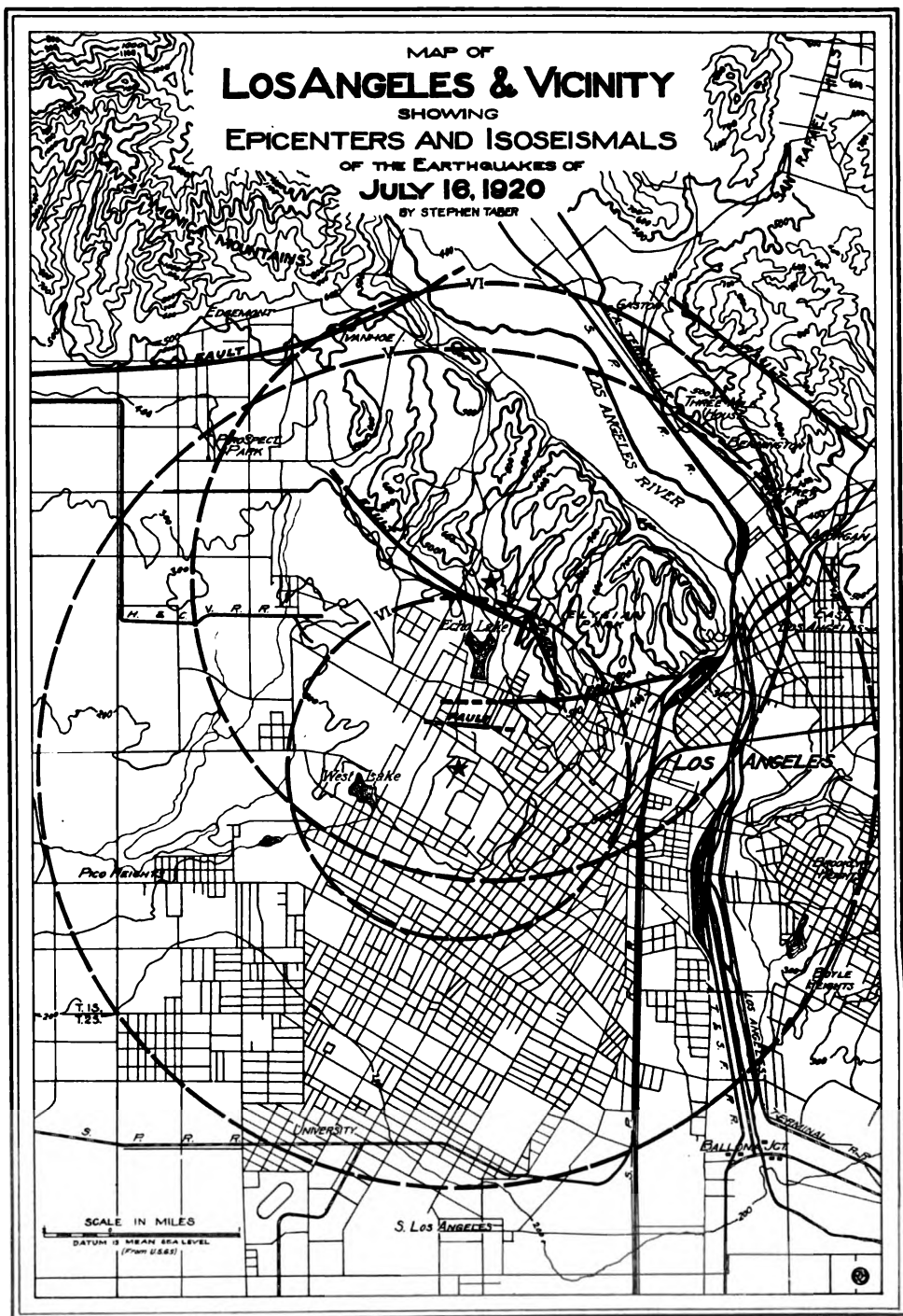
At 10:08 a. m. the largest proportion of overturned bottles was in drug stores located a short distance south of Echo Park; a few bottles were overturned in most of the stores within a radius of one and one-half miles. On the accompanying map (Plate 8) isoseismal VI is drawn around the area within which bottles were overturned. A few objects were overturned outside of the area outlined, but they were either very unstable or were in buildings that were easily swayed.

Four small unstable boxes were overturned in a drug store at the corner of First and Utah Streets, two and one-fourth miles east-south-east of the center of isoseismal VI. This store is in a one-story frame building built on the flood plain of Los Angeles River, and this fact possibly explains the relatively high apparent intensity at this distance from the origin. At a drug store on the hill-slope about one-half mile farther east nothing was displaced.

The maximum epicentral intensity of this shock was a little over VI in the Rossi-Forrel scale. The intensity decreased very rapidly with distance from the origin; in Pasadena, eight to ten miles northeast, the shock was barely felt by a few persons who were favorably situated, and at the Soldiers' Home, eleven miles west, the intensity was about the same. The volt meter at the Soldiers' Home registered this shock as well as the stronger ones in the afternoon. The earthquake was not felt at Mount Wilson or at the beach towns or at other points within a distance of fifteen to twenty miles. The area over which the shock was felt is therefore about 500 square miles.

The afternoon shocks overturned the largest proportion of bottles in drug stores near the intersection of Sunset Boulevard and Lake Shore Avenue. Bottles were thrown down in most of the drug stores within a radius of two and one-half miles, but in most cases the losses were insignificant. The area within isoseismal VI is, therefore, about twice as large as for the morning shock.

The drug store at the corner of First and Utah Streets, which is three miles from the center of isoseismal VI, again showed a higher apparent intensity than its distance from the origin would warrant; two or three dozen bottles and boxes fell from the shelves, a few being thrown down by the shock at 1:27 p. m., but most of them by the shock at 1:30 p. m. At the drug store a half mile farther east nothing fell



at 1:27 p. m., and only one bottle fell at 1:30 p. m., this one having stood with its base partly off the shelf.

The maximum epicentral intensity of the shocks at 1:27 and 1:30 p. m. was between VI and VII, R.-F., only a little higher than for the shock at 10:08 a. m., but they were felt over a larger area, the last shock affecting a much larger area than either of the others.

At Mount Wilson, about fifteen miles from the origin, the shock at 1:27 p. m. was estimated by Mr. W. P. Hoge to have an intensity of II R.-F.⁵ This is the farthest point from which the shock was reported as felt. The total area affected by the shock was, therefore, about 800 square miles.

The shock at 1:30 p. m. had an intensity of about III at Mount Wilson, Azusa, Soldiers' Home, Santa Monica, Long Beach, and other points fifteen to twenty miles from the origin. It was felt by a few persons in a high building at Pomona, twenty-eight miles to the east, and was reported as having been barely felt in Santa Ana, thirty miles to the southeast. The area over which this shock could have been felt was, therefore, about 2,500 square miles.

A study of all the available intensity data indicates that the earthquake at 10:08 a. m. had its epicenter three-quarters of a mile south of Echo Park and that the earthquakes at 1:27 and 1:30 p. m. had their epicenters one-half mile north of the Park. It is possible that the epicenters of the two afternoon shocks did not exactly coincide, but they could not have been far apart. The error in the location of these epicenters, the writer believes, is less than three-fourths of a mile for the morning shock and less than one mile for the afternoon shocks.

AFTERSHOCKS

Following the earthquakes of July 16th a number of shocks were recorded in Los Angeles and the surrounding country during the rest of July and the months of August and September. Most of them had an intensity of less than IV in the Rossi-Forel scale, and only one, that of July 26th, had an intensity as high as V. All of the shocks, with the exception of some of those recorded on the volt meter at the Soldiers' Home near Sawtelle, probably had their epicenters within the city of Los Angeles—most of them were reported only from within the city. While listed in this paper as aftershocks, these slight earthquakes have probably originated along several different faults; they are aftershocks

⁵ *Monthly Weather Review*, 48, 434, July, 1920.

merely in the sense that they belong to a single series and were immediately preceded by earthquakes of higher intensity. All of the earthquakes felt in the Los Angeles district during recent months, and this includes the Inglewood series, are evidently closely related; and, although they have originated in different localities, all of them are believed to be due to the adjustment of stresses set up by the same tectonic movements.

The strongest of the aftershocks recorded in Los Angeles during the recent series occurred at about 4:15 a. m. on July 26th. This shock was investigated in detail by Mr. F. Rolfe and the following account is taken chiefly from his report. Several earthquakes of relatively low intensity were felt during the morning of July 26th, observers differing as to the exact number and as to their relative intensity, though this lack of agreement is to be expected since most people were asleep and the effects of the shocks were slight. The shocks occurring at about 4:15 a. m. were the only ones that were generally observed.

In Los Angeles most people were awakened by the shocks, and some were frightened, but no damage seems to have been caused. In the County Courthouse and the Hall of Records three or four clocks out of a total of about sixty were stopped. In a jewelry store on Third Street, between Flower and Figueroa, an electric clock was stopped, but two ordinary pendulum clocks continued to run. A pendulum clock in a house near the south end of Echo Park was also stopped. The volt meters of the Edison Electric Company in Los Angeles recorded the earthquake, but outside the immediate vicinity of the city the volt-meter records showed little indication of the disturbance. A few loosely piled orange boxes were overturned in the basement of a house in the southwestern part of Los Angeles.

The maximum intensity was a little above V. The isoseismals of this earthquake, as drawn by Mr. Rolfe, were based on about one hundred and fifty individual reports. Isoseismals V, IV, and III are approximately circular and concentric about the business section of Los Angeles. The shock was reported as far north as Sunland and Fernando; toward the east it was felt at Puente, but not at Pomona or Glendora; to the south it was barely noticeable at Compton and toward the west it was felt as far as Venice near Santa Monica. The area over which the shock could have been felt was, therefore, approximately 900 square miles and is apparently a little larger than that for two of the shocks on July 16th which had higher epicentral intensities. This

anomaly may be due to insufficient data from the thinly settled districts or it may be due to the fact that the shock on July 26th came early in the morning, when all was quiet and conditions were favorable for the perception of a feeble vibration.

A list of shocks recorded in Los Angeles and the surrounding country between July 16 and September 30, 1920, is given below. This list is probably incomplete. It includes the shocks recorded on the volt meter at the Soldiers' Home on July 16th, 17th, and 18th; but after the latter date the volt-meter records were not available.

LIST OF SHOCKS RECORDED NEAR LOS ANGELES
JULY 16 TO SEPTEMBER 30, 1920

Date	Time	Intensity	Remarks
July 16	12:30 a. m.	I	Soldiers' Home; recorded on volt meter but not felt.
July 16	12:40 a. m.	I	Los Angeles; recorded on volt meter, 7th floor of Edison Building, corner of Broadway and Third Street. Probably the same as the shock listed above.
July 16	4:30 a. m.	I	Soldiers' Home; recorded on volt meter but not felt.
July 16	10:08 a. m.	VI+	Described in detail in this paper.
July 16	12:19 p. m.	II	Recorded in Los Angeles by F. A. Ralph.
July 16	12:22 p. m.	II	Recorded in Los Angeles by F. A. Ralph.
July 16	1:27 p. m.	VI+	See detailed description in this paper.
July 16	1:30 p. m.	VI-VII	See detailed description in this paper.
July 16	4:49 p. m.	III	Recorded in Los Angeles by F. Rolfe.
July 16	5:15 p. m.	I	Soldiers' Home; recorded on volt meter but not felt.
July 16	6:13 p. m.	IV	Recorded in Los Angeles by F. Rolfe and others.
July 17	12:10 a. m.	I	Soldiers' Home; recorded on volt meter but not felt.
July 17	5:05 a. m.	I	Soldiers' Home; recorded on volt meter but not felt.
July 17	5:10 a. m.	I	Soldiers' Home; recorded on volt meter but not felt.
July 17	1:14 p. m.	I	Soldiers' Home; recorded on volt meter but not felt.
July 18	12:32 a. m.	I	Soldiers' Home; recorded on volt meter but not felt.
July 19	6:48 p. m.	II-III	Recorded by several observers in Los Angeles.
July 20	4:08 a. m.	II	Recorded by several observers in Los Angeles.

July 26	4:12 a. m.	III	Two shocks recorded in Los Angeles by R. F. Young and F. A. Carpenter.*
July 26	4:15 a. m.	IV-V	Shock recorded in Los Angeles by J. M. Bartley, [†] F. Rolfe, and others. This shock may be the same as one of the others listed for July 26th.
July 26	4:20 a. m.	II	Los Angeles; reported by F. A. Carpenter.
July 26	9:02 a. m.	II	Recorded in Los Angeles by F. Rolfe.
July 27	12:02 a. m.	III	Los Angeles; observed by R. F. Young.*
July 27	2:10 a. m.	II-III	Los Angeles; reported by Miss E. F. Fox and F. Rolfe.
July 27	1:35 p. m.	II	Los Angeles; reported by Miss E. F. Fox and Associated Press.
July 27	1:39 p. m.	II	Los Angeles; reported by Miss E. F. Fox and F. Rolfe.
July 27	2:10 p. m.	II	Los Angeles; reported by T. R. Spalding.
July 28	11:25 a. m.	II	Los Angeles; reported by F. A. Carpenter.
July 28	11:28 a. m.	IV	Los Angeles; reported by H. B. Hersey.*
Aug 23	3:10 a. m.	IV	Los Angeles; reported by P. Hansen. [‡]
Sept. 2	8:50 p. m.	II	Los Angeles; three light shocks reported by P. Hansen.*
Sept. 15	4:50 a. m.	II	Los Angeles; three light shocks reported by P. Hansen.*
Sept. 18	3:45 a. m.	III	Los Angeles; felt by several; reported by P. Hansen.*

PHYSIOGRAPHY AND GEOLOGY OF THE EPICENTRAL AREA

The July earthquakes originated near the inner margin of the coastal plain of southern California close to the southwestern base of the Elysian Park hills. These hills extend from the eastern end of the Santa Monica Mountains southeastward for about four miles parallel to the valley of Los Angeles River. On the northeast they descend abruptly to the flat floor of the river valley; their southwestern slope is gentle and imperceptibly merges into the coastal plain. The Santa Monica Mountains, which have an east-west trend, separate the broad San Fernando Valley on the north from the coastal plain on the south. These mountains reach elevations of 1500 to 1800 feet above sea level.

Los Angeles River, which drains the San Fernando Valley, has cut a rather narrow valley or canyon separating the Santa Monica Mountains and Elysian Park Hills on the west and south from the Verdugo Mountains, the San Rafael Hills, and other outliers on the northeast.

* *Monthly Weather Review*, 48, 434, July, 1920.

† *Monthly Weather Review*, 48, 490, August, 1920.

‡ *Monthly Weather Review*, 48, 559, September, 1920.

Where the river debouches from its canyon it has built up an alluvial fan, the upper portion of which is now included within the city of Los Angeles.

The geology of the epicentral area has been studied and mapped in detail by Arnold, and the following description is largely abstracted from his report on the Los Angeles Oil District.⁹

The oldest rocks in the district are found in the Santa Monica and Verdugo Mountains and the northern part of the San Rafael Hills. They consist chiefly of metamorphic and plutonic rocks which are certainly pre-Cretaceous and are probably Jurassic in age. Basalt and diabase of Miocene age occur in the Santa Monica Mountains as intrusions and as surface flows. Tertiary rocks of the Puente (Miocene) and Fernando (Pliocene) formations are exposed in the hilly region comprising the northern portion of Los Angeles and extending as far as the mountains; but toward the south and west they are overlain by Quaternary deposits. The Puente and Fernando formations, consisting chiefly of soft sandstones, shales, and some conglomerates, have a total thickness of over 6000 feet; and, where exposed, they are complexly folded and faulted.

The structural features of the Los Angeles region are attributed by Arnold to two periods of disturbance; one in late middle Miocene, the other in late Pleistocene time. The first resulted primarily in folding with minor faulting along axes that trend approximately N. 60° W., while the last was dominated by faulting along east-west lines. Faults of small displacement, striking in various directions, are common throughout the district. The principal faults mapped or described by Arnold are shown on the accompanying map (Plate 8).

The most prominent fold in the district is the great Elysian Park anticline in Puente sandstone and shale, the axis of which extends in a direction S. 60° E. from a point near Ivanhoe. It is paralleled on the northeast by several folds and at least one prominent fault. Its southwest limb is disturbed by a subordinate syncline accompanied by a zone of faults extending parallel to the main axis a short distance northeast of Echo Park. The epicenters of the afternoon shocks on July 16th were located very close to this fault zone, if not in it.

Another subordinate flexure affecting the southwest limb of the Elysian Park anticline may be traced from the south end of Echo Park westward for a mile and then northwest to a point near Colegrove.

⁹ Ralph Arnold, "The Los Angeles Oil District, Southern California," *United States Geological Survey Bulletin* No. 309, pp. 138-198, 1907.

East of Echo Park it apparently passes into a fault. The Los Angeles oil fields have been developed on the southern limb of this subordinate anticline. South of the anticlinal axis there is a zone of faulting which limits the productive oil fields on the north, and, in places, forms the contact between the Fernando formation on the south and the Puente on the north. The epicenter of the earthquake which occurred at 10:08 a. m., July 16th, as indicated on Plate 8, was close to this line of faulting. The earthquake was probably due to an adjustment along this fault or one of the many small faults that cut the rocks in this vicinity.

"The most prominent structural feature belonging to the east-west Pleistocene system," Arnold states, "is the fault zone extending along the southern face of the Santa Monica Mountains from Los Angeles River at least as far as Hollywood and probably much farther west."¹⁰ It brings the upper Puente shale into contact with the granite, from which it is ordinarily separated by at least 2,000 feet of sandstone and conglomerate. It has been largely instrumental in the formation of the range and is the only fault in the district mapped by Arnold that seems to have appreciably affected the present topography.

The topographic effects of the Santa Monica fault zone are strongly marked because of the recency of the displacements and because of the high resistance to erosion afforded by the crystalline rocks composing the mountain range as compared with the sedimentary strata of the surrounding country. There was certainly no activity along this fault zone at the time of the July earthquakes, for the intensity of the shocks decreased steadily in passing northward toward the mountains. It may be impossible to prove that any particular earthquake, recorded since the settlement of California, has originated along it, yet, on account of its recent formation, it must be regarded as a probable locus of future seismic disturbances. Some of the many shocks recorded at Soldiers' Home may have originated along this fault where it passes just north of that place.

In addition to the major faults and fault zones described above, the Tertiary rock strata in the immediate vicinity of Los Angeles are cut by many minor faults with displacements ranging from less than an inch up to several feet. The principal shocks on July 16th probably originated within or at least very close to the major fault zones, but it is not unlikely that some of the recent disturbances were due to adjustments along minor faults.

¹⁰ Ralph Arnold, *Op. cit.*, p. 156.

Pleistocene deposits, consisting of gravel, sand and clay, cover the Tertiary rocks in the greater part of Los Angeles and in the region lying to the south and west. The thickness of these deposits in the vicinity of the city does not exceed a few hundred feet, but on the plain farther south they extend to a depth of over one thousand feet. Some of the Pleistocene gravel and sand in the northern part of Los Angeles is probably of marine origin; elsewhere in this vicinity the deposits are largely fluvial.

The Pleistocene deposits lying unconformably upon the Tertiary rocks conceal their structure and make the location of faults difficult. In some places, as in the Salt Lake oil field, about five miles west of Los Angeles, the presence of faults in the underlying Tertiary rocks is indicated by petroleum seepages and accumulations of brea; and along the Inglewood-Newport-San Onofre fault zone there is physiographic evidence of post-Pleistocene displacements. There is also physiographic and geologic evidence of post-Pleistocene folding along flexures that originally developed in the Tertiary strata before the Pleistocene beds were laid down.

Orogenic movements have taken place on a grand scale in Southern California since mid-Tertiary time and even since the Pleistocene. Fossiliferous beds of the San Pedro (Pleistocene) formation have been lifted several hundred feet above sea level and subjected to folding and faulting. There is probably no other place in North America where marine beds of Pleistocene age have been disturbed as much as those in the coastal region of southern California.

CHARACTERISTICS OF EARTHQUAKES IN THE LOS ANGELES DISTRICT

A striking characteristic of the earthquakes in southern California is the small size of the areas within which they are perceptible considering their relatively high epicentral intensities. This statement is true not only of the recent earthquakes but also of the other shocks in this section that have been carefully studied, such as the earthquake in the Imperial Valley, June 22, 1915,¹¹ and the San Jacinto earthquake of April 21, 1918.¹² In fact, it seems to be a general characteristic of California earthquakes, including those of higher intensity like that of April 18, 1906. All of the California earthquakes studied by the writer have been felt over areas that are from one-fifth to one twenty-fifth as

¹¹ Carl H. Beal, "The Earthquake in the Imperial Valley, June 22, 1915," *Bulletin of the Seismological Society of America*, 5, 130, 1915.

¹² Sidney D. Townley, "The San Jacinto Earthquake of April 21, 1918," *Bulletin of the Seismological Society of America*, 8, 59, 1918.

large as the areas affected by earthquakes of similar epicentral intensity in the Coastal Plain, Piedmont and Appalachian Mountains provinces of the Eastern States.

The area of maximum intensity of each of the recent shocks was small and apparently circular in form. All of the inner isoseismals were approximately circular. The outer isoseismals were probably nearly circular also, but the scarcity of reports, especially from the thinly inhabited mountain region to the north and east of Los Angeles, makes it impossible to draw them with certainty.

The principal shocks were characterized in their epicentral areas by short, sharp, explosive-like vibrations, which seem to have been chiefly in a vertical direction. At a distance from the origin the motion was a slower oscillation with the horizontal component prominent.

The characteristics outlined above indicate that the recent earthquakes originated relatively close to the surface in the slightly consolidated Tertiary rock strata; and that the displacements which caused the shocks were of very limited extent. The vertical vibrations that seem to have been dominant in the epicentral areas suggest that the displacements were vertical.

FUTURE SEISMIC ACTIVITY IN THE LOS ANGELES DISTRICT

During the last fifty years Los Angeles has grown with great rapidity. It now has a population of over 575,000. Much of the country in the immediate vicinity of the city is densely populated. Therefore, the question of future seismic activity in this district is today a very important one.

The earthquake hazard of a district is indicated by the frequency and intensity of the shocks that have affected it in the past. This method of measurement, however, is likely to be misleading unless the seismic history of the region for a long period of time is known or can be inferred.

A large number of earthquakes have been felt in Los Angeles and vicinity during the last century and a half. Many of the shocks listed in the catalogues compiled by Holden,¹³ McAdie,¹⁴ and Palmer¹⁵ have

¹³ E. S. Holden, "A Catalogue of Earthquakes on the Pacific Coast, 1769 to 1897," *Smithsonian Miscellaneous Collections*, No. 1087, 1898.

¹⁴ A. G. McAdie, "Catalogue of Earthquakes on the Pacific Coast, 1897 to 1906," *Smithsonian Miscellaneous Collections*, No. 1721, 1907.

¹⁵ A. H. Palmer, "California Earthquakes During 1915"; "California Earthquakes During 1916"; "California Earthquakes During 1917"; "California Earthquakes During 1918"; and "California Earthquakes During 1919," *Bulletin of the Seismological Society of America*, 6, 8; 7, 1; 8, 1; 9, 1; and 10, 1.

been recorded in this region; but these lists are incomplete, a large portion of the shocks, especially those of low intensity, having gone unrecorded. In early years the district was very thinly populated; in recent years the population has increased rapidly, but little publicity has been given to earthquakes by California papers. The records, however, are much more nearly complete for the recent years.

The frequency of earthquakes during the latter part of the eighteenth century, a period for which few records have been preserved, is indicated by some of the local names given by the early Spanish explorers. Father Junipero Serra in 1778 referred to the San Gabriel Valley as "El Valle de los Temblores"; San Pedro Bay was known as "Bahia de los Temblores," and there was also in this part of the State a "Rio de los Temblores." The mountains of the Temblor range lie about one hundred miles north of Los Angeles.

Earthquakes occur occasionally in regions of low seismicity, and therefore when a region has been under observation for a relatively short time, a better indication of its true seismicity may be obtained from a study of its geology and physiography. One of the best indications of the seismicity of a region is probably the magnitude of the post-Pleistocene displacements; and measured by this test the southern portion of California would have to be ranked high among the more important seismic districts of America. It is also a region of high relief, and M. de Ballore has shown that high relief is usually associated with high seismicity.

The vast majority of the shocks felt in Los Angeles have been of low intensity; several have had an intensity within the city of between VIII and IX, and have resulted in damage to property; but not one of those recorded has had an intensity of X within the city limits, although some of them have reached that intensity in their epicentral areas a few miles away.

There is every reason for believing that earthquakes will be felt in the Los Angeles district as frequently in the future as in the past, and that the intensity of some of them will be as high as that of any of the earlier shocks.

Many faults have been discovered in the vicinity of Los Angeles; others probably will be revealed when the geologic structure of the country is worked out in greater detail; others are unquestionably buried under the Quaternary deposits. Some of the faults are known

to be active at the present time and others are suspected of being active. It is of the utmost importance that all active faults be located so that engineers and architects can take precautions in the location and construction of aqueducts, buildings, and other structures. This can be done most easily by determining which faults are the loci of the light shocks that occur from time to time.

All of the faults within the city of Los Angeles are relatively short and a short fault is not so likely to be the source of an extensive seismic disturbance. The Inglewood-Newport-San Onofre fault, which was described in a previous paper, seems to have been, in recent years, one of the most active faults in the immediate vicinity of Los Angeles. The fault along the southern base of the Santa Monica Mountains should be watched very carefully for evidence of activity, and the same is true of the great fault along the southern front of the San Gabriel Range. The faults on both sides of the Verdugo Mountains are probably recent in origin but almost nothing is known about them. The San Andreas, San Jacinto, and Elsinore fault zones, three of the longest active faults in southern California, are, fortunately, so far from Los Angeles that earthquakes originating along them lose much of their intensity by the time the vibrations reach the city.

It has been frequently stated that the earthquakes of the Pacific Coast are less destructive than the tornadoes and thunder-storms of the Central and Eastern States and the statement is probably true; but that is no reason for not taking every practicable precaution to prevent damage to property and loss of life from earthquakes. Earthquakes can not be prevented, but with proper precautions their destructive effects can be reduced to a minimum. The people living in California should frankly admit that this is a region of relatively high earthquake frequency; every shock that occurs should be recorded and the epicenter located as accurately as possible so that the active faults can be determined; all of the stronger shocks should be investigated immediately by experienced seismologists and engineers in order to learn as much as possible concerning the character of earthquake motion and of its effects on different types of structures.

SUMMARY

More than a hundred earthquakes have been recorded in southern California during the period February–September, 1920. These earthquakes have originated along several different faults in the vicinity of

Los Angeles, but all of them are believed to have resulted from the adjustment of stresses set up in the region by the same general tectonic movements. The series of shocks felt in Los Angeles on July 16th originated along faults which cut Miocene and Pliocene rocks in the northern part of the city. The three strongest shocks on July 16th had epicentral intensities of between VI and VII in the Rossi-Forel scale; and they were felt over areas of from 500 to 2500 square miles. The known seismic history of southern California and the magnitude of the post-Pleistocene movements both indicate that the seismicity of the region is relatively high. There are many faults in the vicinity of Los Angeles; some of which are known to be active, while others are suspected of being active. Fortunately those within the city are short, while the longer ones are seven to thirty miles away, and are therefore less dangerous in so far as Los Angeles is concerned.

THE APPARENT INTENSITY OF EARTHQUAKE SHOCK IN ALLUVIAL AREAS

By FREDERICK P. VICKERY

The seismologists of California consider it their duty to keep before the public the essential facts concerning earthquakes. While they have had to combat apathy and even assumed indifference, it is seldom that they have been called upon to contradict plausible theories that do not take into account all the observed facts.

A statement has recently been published in one of the daily papers, and copied by an important weekly review, concerning the intensity of earthquake shocks in alluvial areas. The writer of the article states:

California's great valleys, such as the Imperial, San Fernando, San Joaquin, and Sacramento, running north and south and parallel with the Pacific Ocean, were once ocean beds from which the water was excluded by the erosion of the surrounding hills, then thousands of feet higher than at present. The sedimentary deposit thus created not only furnished the base of its present oil fields through the enfoldment of animal and vegetable matter but furnished what might be called a perfect safety valve or giant shock-absorber as against the rigid granite formations of most other parts of the world. Whenever volcanic disturbance occurs at distant points it registers in California by reason of its safe and sensitive structure, just as the needle of the seismograph notes that same disturbance, and therein lies its perfect safety against great disaster. With Mount Lassen serving as a great vent, active as a volcano when required, and silent when the inner earth is normal, no great disaster can occur any more than could a boiler explode with an open vent or safety-valve. The most that can be expected is the mild earth adjustment which naturally follows earth-pressure, or displacement by upheaval or receding faults. . . .

The same geological condition that makes San Francisco safe, as well as sensitive against internal disturbance, applies with equal force to Los Angeles, San Diego, and practically every municipality in California. They may be "shook up" occasionally, but they will never be "shook down," as in the case of Valparaiso and other cities located upon a rigid unyielding granite bed. The fact that a dozen or more tremors have been felt in the last two weeks in what might be called the former ocean bed of the Los Angeles Valley, bounded by the Tehachapi, Sierra Madre and Volcan range of mountains, without being felt beyond those natural barriers, without loss of life in a community of nearly a million people, and with but insignificant destruction of property, is proof positive of the natural adjustment theory—in other words, shock absorption of distant disturbance without either injury or danger.

The author of the above statement apparently is not aware that some of the earthquake shocks, particularly those of Los Angeles, 1920; San Francisco, 1906; and San Francisco, 1868, originated in close proximity to centers of population. Cities are frequently located on alluvium, because the broad flat surface of alluvial soil affords an easy means of transport and communication. Alluvium has two effects on earthquake shocks: first, if the shock is not transmitted by underlying consolidated rock, alluvium will diminish the intensity of a shock transmitted through it, and second, and vastly more important, the apparent intensity and the actual damage are much greater in alluvial areas than would have obtained in similarly located hard rock areas.

The earthquake at Los Angeles was investigated for the Seismological Society by Professor Stephen Taber.¹ In the summary of the report on this investigation, Professor Taber states:

The earthquake of June 21, 1920, originated a short distance west of Inglewood. The maximum intensity of the epicentral area was between VIII and IX in the Rossi-Forel scale. . . .

The area within which the shock was felt (eleven thousand square miles, or twenty-nine thousand square kilometers) was small considering the high intensity of the shock. This probably means that the origin was close to the surface. The rapid decrease in intensity on going away from the epicenter is chiefly due to the unconsolidated character of the rock strata in the area. While the vibrations die out rapidly in passing through such materials the destructive effects are always greater than in areas similarly located with respect to the origin but which are underlain with more rigid rock.

A thorough analysis of earthquake phenomena was made by Professor A. C. Lawson and his associates on the California State Earthquake Investigation Commission. In discussing the mechanics of the earthquake of San Francisco, April 18, 1906, Mr. H. F. Reid makes the following statement:

Experience shows that damage done by destructive earthquakes is much greater on alluvial soil than on solid rock. . . . Probably the best example we have is the city of San Francisco itself, which was built variously on solid rock, on sand, on natural alluvium, and on "made ground." The description of the destruction done in the city shows that within its limits the character of the foundation was a far more potent factor in determining the damage done than nearness to the fault line. This is not a question of transmission of vibrations, for, on account of the higher elasticity of solid rock, it would transmit vibrations far better than alluvium."

¹ Stephen Taber, "The Inglewood Earthquake of Southern California, June 21, 1920," *Bulletin of the Seismological Society of America*, 10, 129.

At a later point in the same chapter Mr. Reid states "that the damage on small marshes may represent an acceleration as much as 12 times as great as on solid rock; on made land, from 4.4 to 11.6 times as great; on loose sand, from 2.4 to 4.4; and on sandstone, from 1 to 2.4. Although it has been well known that the apparent acceleration on soft land is much greater than on rock, the ratios obtained seem very much greater than had been suspected."

In regard to cities situated on alluvium at a considerable distance from the source of the shock, Mr. Reid finds that such cities as Sacramento, San Jose, Willits, and Salinas, as well as the west side of the San Joaquin Valley, suffered from two to sixteen times as intensely as if the ground on which they stood had been solid rock.

The author of the article published in one of our daily papers recognized the dampening effect on earthquake shocks during their transmission through alluvium, but failed to recognize the much more serious increase in the destructive effect of earthquake waves in alluvial areas.

Californians who desire to conserve the property and lives of their children will build on solid rock and use materials known to withstand earthquake shock.

SEISMOLOGICAL NOTES

The first three of these notes were kindly sent by Count de Montessus de Ballore. The translation from the French is hardly literal enough to warrant the use of quotation marks.

Chile, July 26, 1920.—This shock commenced at 0^h 31^m 42^s (75th meridian time), and reached its greatest intensity 22^s afterward. The total duration was 1^m 40^s. The origin was in the valley of Aconcagua, which is the line of least resistance in central Chile, the line along which occurred the earthquakes of August 16, 1906, and all the other shocks of the central region. The maximum intensity of the shock of July 26th was not greater than VI, of the Rossi-Mercalli scale, and yet it was evidenced as far as Buenos Aires with an intensity of II. This is very remarkable because of the distance of about 1200 kilometers separating that city from Santiago. There were no after-shocks. This shock was transverse (across continent).

Chile, August 20, 1920.—The preliminary tremors commenced at 11^h 34^m 5^s and continued 1^m 24^s. The principal oscillations lasted 2^m 7^s with a maximum amplitude of 2250 microns at Santiago where, however, it was not felt. The recorded duration was 30^m 39^s, and during the principal phase the period attained as much as 6^s. Everywhere the horizontal movement predominated over the vertical. This shock was felt from the mouth of the Rio Mataquito, latitude 36°, to the fiord Relonquavi, 41° 3'. At Angol, 37° 48', several public buildings, such as the school, were seriously damaged and several homes more or less completely demolished. On the island of Mocha, latitude 38° 17' to 23', the two lighthouses were badly cracked and put out of service, the tower of the east one threatening to fall. All of the buildings damaged were as defective as it is possible to imagine. On the island of Mocha there were twenty-one after-shocks the same day, many more than on the mainland. At the harbor of Talcahuano the ships at anchor were violently thrown about by the consecutive movements of the waves. The center was therefore submarine. The shock was longitudinal in relation to the coast.

Chile, October 28, 1920.—This earthquake was felt at Santiago with an intensity of II, but not farther south. The first record of the principal phase was at 7^h 53^m 2^s, with the same maximum as the preceding

shock of 2250 microns for the horizontal amplitude, but a vertical amplitude of practically nothing. The duration of the principal phase was $5^m 2^s$, and 32^m for the total time of vibration. A zone of slight destruction extended from Vallenar, latitude $28^\circ 35'$, to Capiapo, $27^\circ 21'$, about 125 km. along the meridian; the damage was again due to the very faulty construction of the buildings, both public and private. It is probable the shock was of the same intensity as far as the latitude of Chanaral, $26^\circ 23'$, although the reports north of Capiapo were very meager, owing to the desert character of the region. This would give a meridional extent of about 240 km. at least, for the epicentral area. No after-shocks recorded. In the north the limit of perceptibility was badly determined for the same reasons. There is reason to believe that it extended as far as Tarapaca, $19^\circ 56'$, which would make a total distance of about 1500 km. along the meridian. This dimension is nothing remarkable for earthquakes of relatively feeble intensity, at least in Chile.

Portugal, November 26, 1920.—Dr. E. Fontseré, Director of the observatory at Barcelona, Spain, has very kindly sent the following note concerning the shock which was felt in Spain and Portugal on November 26th. This shock occurred along the coast of Portugal and the time at the origin was $11^h 37^m 52^s$ (Greenwich Mean Time).

"Dr. Vincente Inglada published a note describing this earthquake in No. 360 of the *Iberica Review*; in this note he gives the data recorded by the Spanish Seismological Stations, as well as the macroseismic information communicated by Dr. A. Ferraz do Carvalho, Director of the Meteorological Observatory of Coimbra. The epicenter lay in the Atlantic Ocean abreast of Oporto, some seventy-five kilometers from the coast. The intensity on the coast was VIII, F.M."

Willows, California, December 29, 1920.—An earthquake of sufficient intensity to arouse all of the inhabitants is reported to have occurred at Willows at 2:15 a. m. on December 29th.

Mendoza, Argentina, December 28, 1920.—Many after-shocks of the destructive earthquake which occurred at Mendoza on December 17th have been reported. A violent shock occurred at 1:55 a.m. December 28th and another at 3:56. Over four hundred persons were estimated to have been killed or injured by the shocks of December 17th. Wide stretches of territory were flooded with water which gushed from crevices opened by the earthquake shocks.

Albania, January 2(?) , 1921.—A dispatch from Paris, under date of January 2nd, states that 14 persons were killed, 300 injured and 10,000 rendered homeless by an earthquake which nearly obliterated the city of Elbassan, Albania. This city is located about fifty miles north of Tepeleni, the center of the region in which occurred the disastrous shocks in December, 1920.

Mendoza, Argentina, January 3, 1921.—Still another strong shock was reported to have occurred at Mendoza on January 3rd, at 3 p.m. The shock had a duration of five seconds and was the worst which had occurred since December. Walls were shaken down but no casualties were reported as most of the population was living out of doors.

Hickman, Kentucky, January 10, 1921.—An earthquake occurred at Hickman on January 10th at 3:54 p.m. The vibrations lasted about four seconds and were very distinct.

Lake George, New York, January 19, 1921.—A dispatch from Glens Falls, N. Y., states that earthquake shocks were felt at Corinth and Lake George and continued for three minutes. The first shocks were felt at Corinth at 5 o'clock (dispatch does not state whether morning or afternoon) and two hours later at Lake George. Houses were shaken so that dishes rattled. The temperature was 15° below zero.

Glens Falls, New York, January 27, 1921.—"Villages in this section were shaken today for the third time in less than two weeks by what was believed to be an earthquake. Large cracks appeared in the ground at several places."

Isthmus of Tehuantepec, February 3, 1921.—A dispatch from Mexico City states that the Isthmus of Tehuantepec was shaken by a severe earthquake on "Thursday night," which destroyed much property. Mount Popocatepetl was said to have been roused into more vigorous activity.

During the early morning hours of February 4th, the seismographs at Washington, D. C., Mobile, Ala., and Santa Clara, Cal., recorded distant shocks which were probably the ones noted above.

Farenza, Italy, February 11, 1921.—A dispatch from Rome reports earthquake shocks at Farenza, province of Ravenna, on the Adriatic Sea, about one hundred miles south of Venice.

China, March 4, 1921.—A United Press dispatch from Shanghai reports that renewed earthquake shocks in the Kansu and Shensi provinces have killed 250,000(?) people.

Fairbanks, Alaska, March 11, 1921.—Earthquakes are reported to have occurred at Fairbanks at 10 p.m. on March 11th, causing buildings to tremble and windows to rattle.

Terre Haute, Indiana, March 14, 1921.—An earthquake was reported as felt at Terre Haute and vicinity at 6:15 a.m. on March 14th. No damage resulted.

Yuma, Arizona, March 24, 1921.—A shock, continuing for two minutes, was felt at Yuma between 5:30 and 6:00 p.m. on March 24th. There was no damage.

San Juan del Sur, Nicaragua, March 28, 1921.—A strong shock lasting twenty seconds was felt at San Juan del Sur at 2 a.m. on March 28th. Earth tremors from a distant source were recorded on the seismographs at Santa Clara, Cal., and Washington, D. C., in the early morning hours of the same date.

A New Seismograph.—The following notes on seismology have been taken from the report of the Government Astronomer, Hector Observatory, Wellington, New Zealand:

"An order has been placed for a new Milne-Shaw seismograph to be installed at this observatory. This will provide for one horizontal component. To complete the installation another Milne-Shaw seismograph for the other horizontal component, and a vertical component seismograph, are required.

An improvement has been made in the time control of the seismograph by putting in a switch on the lighting circuit. The seismograph light is cut off by hand by this switch five times a day, so that these accurate signals on the seismogram are used to check the time on the record. The signals are made from the standard clock, and are always accurate to the nearest second of time. The new seismograph-detector has been photographed on glass, and is used on the records to assist in the identification of the various earth-waves. Its use has already proved a

great economy in these investigations, and has materially reduced the time formerly taken to interpret the records. The tilt of the ground is frequently recorded on the seismograms, and to obtain an independent check of this, sensitive spirit-levels have been mounted east and west and north and south on the seismograph table, and are read daily. Already many evidences of tilt have been obtained."

Stereographic Projection Map of the World.—The Seismological Society has recently received a stereographic projection map of the world, made by Ernest H. Hodgson, of the Dominion Observatory, Ottawa, Canada. The radius of the projected equator is ten centimeters and the map is intended to be used in determining the geographical coördinates of the epicenter of an earthquake, by the methods explained by Dr. Klotz in his "Seismological Tables," published in volume 3, number 2, of the *Publications of the Dominion Observatory*.

SEISMOLOGICAL REPORTS RECEIVED

AMERICA

Cambridge, Mass.—Seismographic Station, Harvard University. Reports from August 1, 1920, to September 30, 1920.

Denver, Colo.—Jesuit Seismological Service, Sacred Heart College. Report No. 12, December 1 to 31, 1920; Reports Nos. 2 and 3, February 1 to March 31, 1921; Seismic Record No. 1, February 7, 1921.

Ithaca, N. Y.—Seismograph Station, Cornell University. Reports Nos. 110 to 112, December 1, 1920, to February 28, 1921.

Ottawa, Canada.—Earthquake Station, Dominion Observatory. Reports Nos. 21 to 23, December 1 to 31, 1920; Reports Nos. 1 to 9, January 1 to March 31, 1921.

Washington, D. C.—Seismological Bulletin of Georgetown University, Nos. 69 and 69 bis, December 1 to 31, 1920; No. 60, January 1 to 31, 1921; compiled press dispatches from December 5, 1920, to January 27, 1921.

ASIA

Zi-Ka-Wei, China.—Bulletin Sismique de l'Observatoire de Zi-Ka-Wei, Nos. 6 to 12, July 6 to December 28, 1920.

EUROPE

Brussels, Belgium.—Bulletin Sismique de l'Observatoire Royal de Belgique, No. 6, October 22 to December 31, 1920, and supplement, October to December, 1920.

Coimbra, Portugal.—Boletim Sismico do Observatório Meteorológico da Universidade, Nos. 7 to 12, July 1 to December 31, 1920.

Dyce, Aberdeen, Scotland.—Seismological Bulletin, October to December, 1920.

Hamburg, Germany.—Monatliche Mitteilungen der Hauptstation für Erdbebenforschung am Physikalischen Staatslaboratorium, Nos. 10 to 12, October 1 to December 31, 1920.

Blackburn, England.—Earthquake Records, Stonyhurst College Observatory, June 2 to December 30, 1920.

PHILIPPINE ISLANDS

Manila, P. I.—Seismological Bulletin of the Observatory, Nos. 20 to 28, September 1 to December 31, 1920.

MEETING OF THE SEISMOLOGICAL SOCIETY OF AMERICA

A joint meeting of the Seismological Society of America and the Cordilleran Section of the Geological Society of America was held in Berkeley on March 26, 1921. The seismological part of the program consisted of a paper by Professor Bailey Willis, on the "Mechanics of the San Andreas Fault."

Dr. Willis has kindly furnished the following abstract:

The San Andreas Fault, along which occurred the movement which in 1906 gave rise to the San Francisco earthquake, is recognized to be an effect of pressure exerted in rock masses below the surface. The fault may therefore be classed as a compression fault or upthrust fault.

Compression faults, when they originate in deeply buried elastic rock masses, may be ascribed to shearing strains, in accordance with sound mechanical principle, and the direction of strain being observed the direction of the effective pressure may be deduced. It has been shown by Reid¹ and Lawson² that the earthquake shock of 1906 was an elastic rebound, which resulted from a gradual accumulation of strain up to the point of rupture and in a partial elastic recovery of position when rupture took place. The movement of 1906 was thus located in elastic rock masses and corresponded in character to a slight dislocation on a plane of shear, which according to mechanics, would be oriented at an angle of 45° to the effective pressure in an ideally brittle substance. Since rocks are not ideally brittle the angle between the shear and the force would probably be greater.

¹ Reid, H. F., "The Elastic Rebound Theory of Earthquakes," *Univ. of Calif. Publications. Bull. Dept. of Geology*, 6, No. 19. 1911.

² Lawson, A. C., "Mobility of the Coast Ranges of California," *Univ. of Calif. Publications, Bull. of the Department of Geology*, 12, No. 7, pp. 431-473. 1921.

Without going into a discussion of the possible number of shearing planes which may be produced by a definite pressure in an ideal case, it may be said that in a case like that of the San Andreas fault, three sets of planes may develop. To illustrate: A pressure directed in a horizontal plane from S.W. to N.E. could produce an East-West set of shearing planes, a North-South set, and a set trending N.W.-S.E., but dipping 45°, more or less, to the S.W.

Considering these principles and facts, it seemed worth while to test the hypothesis that the San Andreas fault is an effect of compression by examining the rocks adjacent to it with reference to the joints developed in them by shearing. An exceptionally good opportunity to do so is afforded by the Logan quarry, situated on the Pajaro River east of Watsonville, in Santa Cruz County. The facts are briefly as follows:

Logan quarry is opened in a mass of diorite close to the San Andreas fault, which runs along its eastern side and separates the diorite from Tertiary (Monterey) shales. The diorite, a deep-seated rock, has been exposed by erosion because of the uplift of the block southwest of the fault.

The Monterey shales northeast of the fault are closely plicated and overthrust, and thus give evidence of compression in post-Monterey movements. The diorite southwest of the fault exhibits three sets of fractures of different ages, namely:

- Set *A*. Strike N. 67° W. dip 85° S.W.
Strike N. 25° E. dip 55° N.W.
Obtuse angle 92° .
Bearing of line bisecting obtuse angle N. 69° E.
- Set *B*. Strike N. 3° W. dip 63° W.
Strike E.-W. dip 90° .
Obtuse angle 93° .
Bearing of line bisecting obtuse angle N. $43\frac{1}{2}^{\circ}$ E.
- Set *C*. Strike N. 47° W. dip 28° S.W.

San Andreas Fault. Strike N. 51° W. dip 90° in this immediate section.

The systems of shearing in the diorite exhibit certain relations of age: The set *A* is associated with gash veins containing aplite and may therefore be referred to the stage of intrusion and cooling of the diorite. The set *B* cuts set *A* and certain fissures of *B* are filled with basic intrusives which may be contemporaneous with, or younger than, the fissuring. The fractures pertaining to the set *C* are low-angle thrust faults which displace the basic dikes of *B*. Their strike, N. 47° W., is at right angles to the bearing, N. $43\frac{1}{2}^{\circ}$ E., of the force which would produce the shears of the set *B*, and thus *B* and *C* are referable to a common force.

The San Andreas fault is parallel in strike with the low-angle thrusts of *C*, but has a vertical dip. The stratigraphic relations require that it should be regarded as an upthrust from the southwest. When so regarded it is attributable to a compression in the same strike as the pressure which produced the shears of *B* and the low-angle thrusts of *C*.

It is therefore concluded that the structural evidences observed in Logan quarry and vicinity support the hypothesis that the San Andreas fault is a compression fault and that the force which caused it has acted in nearly the same direction since the date of intrusion of the diorite. That date is ancient, even geologically. The diorite may belong to the Mesozoic, or if it is, as is thought, a part of the Santa Lucia series, it may be pre-Cambrian.

MINUTES OF THE MEETING OF THE BOARD OF DIRECTORS
OF THE SEISMOLOGICAL SOCIETY OF AMERICA
FEBRUARY 7, 1921

In the absence of the President, the meeting was called to order by Vice-President Willis at 3 p. m. in the rooms of the Engineers' Club, 57 Post Street, San Francisco, Cal. Directors Lawson, Townley, and Willis were present.

Various matters were considered by the Board and disposed of as indicated under the following heads:

(a) The minutes of the meeting of the Board of Directors of April 12, 1920, were read and approved.

(b) The Secretary reported that he had taken the liberty of appointing a Nominating Committee consisting of R. S. Holway, Chairman; Bernard Benfield, José Costa, A. H. Palmer, and J. A. Taff.

(c) A Board of Election was appointed consisting of the following members: D. S. Richardson, Chairman; F. V. Cornish, S. Einarsson, John F. Forbes.

(d) The following named persons (seventy in number) were elected to membership in the Society:

C. E. Adams, Wellington, N. Z.	H. E. Green, Sonora, Mexico.
George G. Anderson, Los Angeles, Cal.	Oskar Hecker, Jena, Germany.
S. O. Andros, Galesburg, Ill.	Robert T. Hill, Los Angeles, Cal.
John J. Backus, Los Angeles, Cal.	Sumner P. Hunt, Los Angeles, Cal.
P. R. Beamish, Los Angeles, Cal.	Josef J. Johnson, Los Angeles, Cal.
John F. Blackburn, Los Angeles, Cal.	Reginald D. Johnson, Pasadena, Cal.
George F. Bovard, Los Angeles, Cal.	Dr. A. Halden Jones, Los Angeles, Cal.
F. P. Brackett, Claremont, Cal.	C. W. Judd, Los Angeles, Cal.
Earl Campbell, Los Angeles, Cal.	Mrs. Anna Josephine Kareberg, San Francisco, Cal.
Ford A. Carpenter, Los Angeles, Cal.	Ralph Z. Kirkpatrick, Balboa Heights, Canal Zone.
Alvin B. Carpenter, Hollywood, Cal.	Koebig & Koebig, Los Angeles, Cal.
M. C. Chittenden, Los Angeles, Cal.	R. J. Kövesligethy, Budapest, Hungary.
W. H. Code, Los Angeles, Cal.	C. B. Lastreto, San Francisco, Cal.
Prof. C. W. Cook, Los Angeles, Cal.	Charles H. Lee, Berkeley, Cal.
Ramon Gandia Cordovia, San Juan, Porto Rico.	Wayne Loel, Los Angeles, Cal.
William N. Cummings, Orange, Cal.	Burdett Moody, Los Angeles, Cal.
B. L. Cunningham, Los Angeles, Cal.	Don D. Morgan, Los Angeles, Cal.
W. T. W. Curl, Los Angeles, Cal.	S. B. Morris, Pasadena, Cal.
E. K. Davis, Los Angeles, Cal.	S. W. Mudd, Los Angeles, Cal.
F. G. Dessery, Los Angeles, Cal.	Saemontaro Nakamura, Tokyo, Japan.
Leland A. Dubbs, Los Angeles, Cal.	Wilbur A. Nelson, Nashville, Tenn.
Victoria Ellis, Los Angeles, Cal.	Rev. Manuel Ma. S.-Navarro Neumann, S. J., Granada, Spain.
Stuart W. French, Pasadena, Cal.	
H. C. Gardett, Los Angeles, Cal.	

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| Dr. Thomas W. O'Reilly, Los Angeles, California. | Howard E. Simpson, Grand Forks, North Dakota. |
| Charles Oster, Los Angeles, Cal. | Dr. L. B. Stookey, Los Angeles, Cal. |
| Harold S. Palmer, Honolulu, Hawaii. | Oscar Stromborg, Los Angeles, Cal. |
| Edward J. Porteous, Lompoc, Cal. | C. R. Sumner, Los Angeles, Cal. |
| R. H. Postlethwaite, Coachella, Riverside County, Cal. | Franklin Thomas, Pasadena, Cal. |
| Arthur J. Potts, Birmingham, England. | H. J. Tompkins, Pasadena, Cal. |
| Ralph J. Reed, Los Angeles, Cal. | William B. Tuthill, New York, N. Y. |
| Homer I. Reynolds, San Diego, Cal. | David White, Washington, D. C. |
| W. J. Saunders, Los Angeles, Cal. | Walter T. Whitney, Pasadena, Cal. |
| E. F. Scattergood, Los Angeles, Cal. | G. Benton Wilson, Los Angeles, Cal. |
| J. J. Shaw, West Bromwich, England. | W. E. Wrather, Dallas, Tex. |
| E. G. Sheibley, Los Angeles, Cal. | Oswald F. Zahn, Los Angeles, Cal. |

(e) The Instituto Geologico de Mexico was placed on the list of subscribers to the BULLETIN of the Society.

(f) The Secretary reported the death of six members of the Society:

- Maxwell Hall of Jamaica, W. I.
- Homer Hamlin of Los Angeles, Cal.
- Orlis I. Kennedy of San Bernardino, Cal.
- Curtis H. Lindley of San Francisco, Cal.
- H. F. Perry of Palo Alto, Cal.
- L. V. Pirsson of New Haven, Conn.

(g) The Secretary also reported the resignation of four members of the Society: Rev. Ricardo Cirera, A. J. Eddy, J. D. Maddrill, and William F. Prouty; and the withdrawal of the Observatorio Astronomico, Madrid, Spain, from the list of subscribers to the BULLETIN, and also the dropping of nine members for the non-payment of dues.

(h) The Secretary reported a gift of \$451.79 from Dr. J. C. Branner to help pay the cost of printing the June and September (1920) numbers of the BULLETIN; also a further grant of \$200 from the Committee on Grants of the American Association for the Advancement of Science to be used in the immediate investigation of earthquakes occurring on the Pacific Coast of North America; also a grant, not to exceed \$300, from the National Research Council to help defray the cost of printing the December (1920) number of the BULLETIN; and also a grant, the exact amount of which has not yet been determined, from the Hawaiian Volcano Observatory to be used toward the cost of printing Dr. Jaggar's article on the "Seismometric Study of the Hawaiian Lava Column," printed in the December (1920) number of the BULLETIN. The Secretary was directed to send letters of appreciation, on behalf of the Board of Directors, to these benefactors of the Society.

(i) The Secretary proposed two amendments to the By-Laws of the Society which would increase the dues and the price of subscription to the BULLETIN from two to three dollars per year. After considerable discussion and the reading of letters from absent members of the Board of Directors the plan was approved, and it was ordered that the proposition be submitted to a

vote of the members of the Society at the time of the annual election to be held on April 2, 1921, provided it meets with the approval of the officers of the Southwest Section of the Society. Dr. Willis thought that raising the dues to three dollars was hardly fair to the new members who have just joined on the understanding that the dues are to be two dollars per year.

(j) The Secretary spoke of the formation in Los Angeles of the Southwest Section of the Seismological Society, and suggested that a short account of the activities of this Section be printed in the March number of the *BULLETIN*.

(k) The question of holding a meeting of the Society in August, 1921, in conjunction with the meeting of the Pacific Division of the American Association for the Advancement of Science was brought up, and it was decided that such a meeting should be held and that notices of the meeting should be sent out with the ballots for the annual election.

(l) In response to a letter written by Dr. J. C. Branner on July 6, 1920, the National Research Council, on December 14, 1920, appropriated a sum of \$250, to be used by the Seismological Society in the investigation of earthquakes. As the Society already has a fund for this purpose, provided by the Committee on Grants of the American Association for the Advancement of Science, it was decided to accept the grant from the National Research Council on condition that the money was to be called for only in case of emergency, when the funds provided by the American Association should prove insufficient for the investigations in hand.

(m) The Secretary was authorized to have cards printed to be used in collecting data concerning earthquakes occurring in the region of the Pacific Coast of North America.

Adjourned at 4:45 p. m.

S. D. TOWNLEY,
Secretary.

ROSSI-FOREL SCALE OF EARTHQUAKE INTENSITIES

- I. **Microseismic shock:** recorded by a single seismograph or by seismographs of the same model, but not by several seismographs of different kinds; the shock felt by an experienced observer.
- II. **Extremely feeble shock:** recorded by several seismographs of different kinds; felt by a small number of persons at rest.
- III. **Very feeble shock:** felt by several persons at rest; strong enough for the direction or duration to be appreciable.
- IV. **Feeble shock:** felt by persons in motion; disturbances of movable objects, doors, windows; creaking of ceilings.
- V. **Shock of moderate intensity:** felt generally by everyone; disturbance of furniture, beds, etc., ringing of swinging bells.
- VI. **Fairly strong shock:** general awakening of those asleep; general ringing of house bells; oscillation of chandeliers; stopping of pendulum clocks; visible agitation of trees and shrubs; some startled persons leave their dwellings.
- VII. **Strong shock:** overthrow of movable objects; fall of plaster; ringing of church bells; general panic, without damage to buildings.
- VIII. **Very strong shock:** fall of chimneys, cracks in walls of buildings.
- IX. **Extremely strong shock:** partial or total destruction of some buildings.
- X. **Shock of extreme intensity:** great disaster, buildings ruined, disturbance of the strata, fissures in the ground, rock-falls from mountains.

Bulletin of the Seismological Society of America

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 JUNE, 1921

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No. 2

ON SCALES OF SEISMIC INTENSITY AND ON THE CONSTRUCTION AND USE OF ISOSEISMAL LINES

By CHARLES DAVISON

All seismologists who have studied the earthquakes of any district or a given earthquake in detail have been impressed with the need of some scale of seismic intensity. Indeed, several of the scales here given (for instance, those of Egen, Mallet, Baratta, Riccò, and Oldham) were devised for use in the investigation of a particular earthquake.

Even when no definite scale has been used, the compilers of our best earthquake catalogues have evidently had some unexpressed standards in their minds. The terms which they employ may not have been defined with any precision or arranged mentally in any very definite order. But, when the intensities of the earthquakes according to, say, the Rossi-Forel scale can be assigned, it will be found that, though some terms have a range of two degrees of the scale, there is as a rule not much variation noticeable under any particular heading. As all compilers employ similar terms, it will be sufficient to quote one series of epithets. That used by Mallet in his "Catalogue of Recorded Earthquakes"¹ is given, as it is the most extensive. Mr. T. Oldham's "Catalogue of Indian Earthquakes" or Professor Holden's "List of Recorded Earthquakes in California, etc.," only differ from Mallet's in the absence of some of the expressions. I have arranged the terms in a rough order of intensity, prefixing the approximate equivalent according to the Rossi-Forel scale²:

- II. Almost imperceptible.
- III. Very slight, very feeble, perceptible.
- IV. Slight, feeble, weak, gentle, little, trifling.
- V. Moderate, rather strong, rather smart, pretty smart, very perceptible.
- VI. Smart, sharp.
- VII. Strong, heavy, rather severe.

¹ British Association Report, 1852, pp. 1-176; 1853, pp. 118-212; 1854, pp. 1-326.

² I have omitted all such terms as frightful, tremendous, dreadful, terrible, formidable, most alarming, etc.

VIII. Very smart, very sharp,*intense, rather violent.

IX. Very strong, very severe, violent, great.

X. Very violent, destructive, disastrous, most destructive, most disastrous.

The ideal scale of seismic intensity fulfills three purposes: (1) to measure the relative order of intensity of the earthquakes of a given district; (2) to measure that of the earthquakes of different districts; and (3) to trace the variation in the intensity of a particular shock throughout its disturbed area. The use of accurately constructed seismographs might possibly give measurements of greater precision, but such instruments can not at present be erected in sufficient numbers to serve the above purposes. As I have said elsewhere,³ "the superiority of a simple scale . . . lies entirely in the fact that by its means we can obtain a large number of observations of the intensity from within a limited area."

TESTS OF A SEISMIC SCALE

As far as possible, every scale of seismic intensity should satisfy the following conditions:

(1) Each degree of a scale should represent a constant intensity. It should depend on the mechanical effects of the shock, and not on such personal impressions as may vary in different countries and with different observers in the same country or with the same observer at different times. Consider, for instance, such a test as "some startled persons leave their dwellings." It occurs in the sixth degree of the Rossi-Forel scale, which was devised for the earthquakes of Italy and Switzerland. Yet, in another country, an earthquake of intensity VIII would not have this effect; while, in a third, a shock of intensity III has been found sufficient. Even mechanical effects, however, are not always constant, for a shock that would cause widespread ruin among the villages of Sicily might be attended with little damage to the well-constructed cities of Japan.

(2) Each degree should consist of one test only, unless the exact equivalence of two or more tests for one degree has been determined. And it should be mentioned that the only satisfactory mode of proof, apart from seismographic evidence, would be to draw separately the isoseismal lines for each test of a degree and to show that they coincide.

³ *Philosophical Magazine*, 50, 44. 1900.

(3) The degrees of a scale should be so far apart that an intelligent observer should have no difficulty in distinguishing between the tests of successive degrees.

(4) And yet they should be close enough to be applicable to the earthquakes of any country and to shocks of all degrees of strength.

(5) Lastly, as the scales are only used for perceptible shocks, it seems unnecessary to retain the first degree of many scales—the degree which corresponds to shocks that are recorded by instruments only—unless it should be provided, as was no doubt the original intention, that the seismographs should be so adapted as to respond to rapid vibrations only.

SCALES OF SEISMIC INTENSITY

(1) *Brooks Scale*.⁴

B. Cassidy, "History of Louisville from its earliest settlement till the year 1852," Louisville, 1852, pp. 121-126; quoted by Myron L. Fuller, "The New Madrid Earthquake," *United States Geological Survey Bulletin*, No. 494, p. 33. 1912.

This is, I believe, the earliest definite scale of seismic intensity. It dates from 1811-12, the years of the great series of New Madrid earthquakes. Mr. Jared Brooks lived at Louisville, a short distance from New Madrid. During the years mentioned he kept a systematic record of the earthquakes, and in this he divided the shocks into the classes given below. It is interesting to notice that this early scale is the only one in which the long-continued action of the shock is taken into account.

First rate. Most tremendous, so as to threaten the destruction of the town, and which would soon effect it should the action continue with the same degree of violence; buildings oscillate largely and irregularly and grind against each other; the walls split and begin to yield; chimneys, parapets, and gable ends break in various directions and topple to the ground.

Second rate. Less violent but very severe.

Third rate. Moderate but alarming to people generally.

Fourth rate. Perceptible to the feeling of those who are still and not subject to other motion or sort of jarring that may resemble this.

Fifth rate. Not defined.

Sixth rate. Although often causing a strange sort of sensation,

⁴Following M. de Montessus de Ballore ("La Science Séismologique," Chapter I), the scale, whenever possible, is named after its author.

absence, and sometimes giddiness, the motion is not to be ascertained positively, but by the vibrators or other objects placed for that purpose.

(2) *Egen Scale.*

Poggendorff's Annalen der Physik und Chemie, 13, 153-163. 1828.

I am indebted to M. de Montessus de Ballore's "*La Science Séismologique*," page 47, for reference to this early scale. It was devised in order to trace the variation in intensity of the Netherlands earthquake of February 23, 1828, throughout its disturbed area. As M. de Montessus de Ballore remarks, it resembles closely the lower degrees of the Rossi-Foré scale (No. 11), which it forestalls by half a century. On the map which accompanies Egen's paper, the names of the places at which the intensity was 6 or 5 are underlined in red, those at which it was 4 or 3 in blue, and those at which it was 2 or 1 in yellow. Isoseismal lines are not shown on the map; indeed, the observations are too few to allow them to be drawn accurately, but it seems probable that Egen drew at least the innermost isoseismal, for he remarks that the places at which the intensity was 6 lie within an elliptical area, the longer axis of which is directed east and west. So far as I know, Egen's map is the first in which any attempt is made to depict the variation in the intensity of an earthquake throughout its disturbed area. Egen's scale is as follows:

1. Only very slight traces of the earthquake are sensible.
2. A few persons, under favorable conditions, feel the shock; glasses close together jingle, small plants in pots vibrate; hanging bells are not rung.
3. Windows rattle, house-bells are rung; most persons feel the shock.
4. Slight movement of furniture; the shock in general so strong that it is felt by everyone.
5. Furniture shaken strongly, walls are cracked, only a few chimneys thrown down, the damage caused being insignificant.
6. Furniture shaken strongly; mirrors, glass and china vessels broken; chimneys thrown down, walls cracked or overthrown.

(3) *Macfarlane Scale.*

British Association Report, 1842, p. 93.

On October 23, 1839, the increasing activity of the well-known seismic center of Comrie in Perthshire culminated in an earthquake of intensity VIII (Rossi-Foré scale). This earthquake was succeeded by a large number of aftershocks which lasted for several years. These

were carefully recorded by Mr. Macfarlane, postmaster of Comrie, on behalf of a British Association Committee, of which Mr. David Milne (afterwards Milne-Home) was secretary. In order to estimate the relative intensity of the aftershocks, Macfarlane devised an arbitrary scale ranging from 1 to 10, the intensity 1 corresponding to the slightest perceptible shock, and the intensity 10 to the principal earthquake of October 23, 1839. The mode of determining the intermediate degrees is not explained, and thus, though Macfarlane's tables give approximately the relative intensity of the different shocks, they serve no other purpose, for the scale could only be used by himself. It is of interest, however, as an early attempt to meet a distinct need.

(4) *Mallet Scale. I.*

British Association Report, 1858, p. 59.

In his fourth report "On the Facts of Earthquake Phenomena" (pp. 1-136), Mallet included his well-known "Seismographic Map of the World" (plate 12). The method of coloring this map was based on his division of all the earthquakes recorded in his great catalogue into three classes:

1. Great earthquakes, being those in which, over large areas, numerous cities, etc., were overthrown, multitudes of persons killed, rocky masses dislocated, and powerful "secondary effects" produced.

2. Mean earthquakes, or those which, although perhaps having a wide superficial area, were recorded to have produced much less destructive effects upon cities, etc., and little or no changes upon natural objects, and scarcely any loss of life.

3. Minor earthquakes, limited to those which, although sensible and producing in their full development some effects (fissures, etc.) upon buildings, did not affect natural objects at all, and left few or no traces of their occurrence after the shock.

(5) *Mallet Scale. II.*

"The Great Neapolitan Earthquake of 1857," 2, 253-256. 1862.

In his important investigation of the Neapolitan earthquake of 1857, Mallet's studies were confined for the most part to the area of destruction. The variation in the intensity of the shock is represented by a series of isoseismal lines corresponding to five degrees of intensity; and, so far as I know, this is the first occasion on which the variation has been so represented. The scale is given by Mallet in two slightly different forms (pp. 253 and 255). In the following table both these forms are included, the tests (a) under each degree being those

on page 253, and the tests (b) those on pages 255-256.

5. (a) The wave sensible, even to the instrumental delicacy as a seismometer, of Padre Secchi's floating barometer at Rome; (b) the shock easily perceived by instrumental disturbance.

4. (a) The shock perceived by the unassisted senses; (b) the shock distinctly perceived by the unassisted senses and producing more or less alarm.

3. (a) The effort limited to the production of fissures and slight dislodgments in buildings, no loss of life; (b) partial prostration and universal fissuring of edifices, with partial or no loss of life.

2. (a) Large portions of cities and towns thrown down, persons killed and wounded by their fall; (b) great prostration of edifices and loss of life.

1. (a) The greater portion of the cities and towns perfectly prostrated; (b) general total destruction of edifices and great loss of life.

(6) *Williamson Scale.*

Quoted by H. O. Wood, *Bulletin Seismological Society of America*, 4, 178. 1914.

In his valuable paper "On the Earthquakes of 1868 in Hawaii" (pp. 169-203), Mr. Wood gives a list of earthquakes observed in 1868 by the Rev. G. Williamson in the district of Kona, Hawaii. Mr. Williamson classified the shocks with regard to intensity as follows:

Very light; light; moderate; heavy; very heavy; very, very heavy. Instead of representing the different degrees of this scale by numbers, he used the initial letters: VL, L, M, H, VH, VVH. The scale is obviously open to the same objection as the Macfarlane scale (No. 3).

(7) *Saderra Masò Scale.*

P. Miguel Saderra Masò, "La Seismogia en Filipinas," p. 21, Manila, 1895.

This scale has been in use in the Philippine Islands since 1870. It is given in the form of adjectives alone, which, like the preceding scale, would have conveyed no definite meaning had not the author subsequently given their equivalents in terms of the Rossi-Forel scale. It is thus merely a somewhat rough scale, adapted for use in a sparsely populated country, and formed in a few cases by grouping together successive degrees of the Rossi-Forel scale.

1. Perceptible (II, III).
2. Slight (IV).
3. Ordinary (V).
4. Strong (VI, VII).

5. Violent (VIII).
6. Destructive (IX, X).

(8) *De Rossi Scale.*

Bullettino del Vulcanismo Italiano, anno 1, 1874, p. i; anno 2, 1875; p. iii; anno 3, 1876, p. i; anno 4, 1877, pp. 39-40; anno 5, 1878, p. 46.

The earliest form of this scale was devised towards the close of 1873 by the late Prof. M. S. de Rossi, director of the geodynamic observatory of Rocca di Papa near Rome. In the following year, de Rossi began the issue of his journal, the *Bullettino del Vulcanismo Italiano*, and in the first volume he published a list of the Italian earthquakes of the year 1873. In order to state the intensity of each shock with some precision, he endeavored to give to every adjective used a definite meaning, and this was the origin of the scale which bears his name. Though the degrees of the scale were numbered, de Rossi employed in his lists the corresponding adjectives. It is evident that his first thought was to frame a scale to be used in comparing the intensities of different earthquakes, rather than to aid in representing the variation of intensity of each earthquake throughout its disturbed area. I give first the earliest form of the scale, which contains ten degrees. It is applicable to shocks of every degree of strength, and must certainly be regarded as a great advance on its predecessors.

1. Very slight shock, recorded by seismographs or by one seismologist.
2. Weak shock, felt by more than one.
3. Slight shock, felt by many.
4. Sensible shock, accompanied by shaking of fastenings, chandelier-prisms and furniture.
5. Moderate shock, felt generally by very many persons.
6. Rather strong shock, ringing of bells, oscillation of lamps, stopping of clocks.
7. Strong shock, fall of plaster, ringing of church bells, noise.
8. Very strong shock, fall of chimneys and cracks in buildings.
9. Ruinous shock, total or partial fall of some buildings.
10. Disastrous shock, great ruins and loss of life.

In subsequent years, de Rossi modified the degrees of his scale (except those numbered 1, 2, 9 and 10) by the addition of new tests. It is unnecessary to trace the changes in the scale from year to year. The degrees 3-8, as given in the version of 1878, are as follows:

3. Slight shock, felt by many persons, or announced in the newspapers or by those who are not seismologists, and of which the duration or direction may be easily estimated.

4. Sensible shock, making fastenings, chandelier-prisms and furniture shake, creaking of floors.

5. Moderate shock, felt generally by very many persons, making a few bells in towns ring; felt by those who are not seismologists in many places not very near together, causing beds to shake; alarm among animals.

6. Rather strong shock, with more or less general ringing of bells, oscillation of lamps, stopping of clocks, in towns; and, in the country, visible or sensible quivering of trees or shrubs; some persons say that fortunately no damage occurred; through fear or prudence, some go out into the open air; almost general interruption of sleep at night.

7. Strong shock, with fall of plaster, ringing of church bells, noise and general alarm, without damage; fall of objects and pictures.

8. Very strong shock, with fall of chimney-pots, cracks in buildings, flight of persons from houses.

(9) *Forel Scale.*

Archives des Sciences Physiques et Naturelle (Geneva), 6, 465-466. 1881.

In 1878, the Helvetic Society of Natural Sciences appointed a committee for the study of earthquakes in Switzerland. From the first, a prominent part in the work of this committee was taken by Professor F. A. Forel of Lausanne, who, unaware of the existence of the de Rossi scale, proposed the following scale. This also consists of ten degrees, and, though some degrees depend on personal impressions, they are more definite than those referred to in the de Rossi scale.

1. Shock of microseismometric order.

2. Extremely feeble shock, recorded only by seismometers.

3. Very feeble shock, perceptible to a person awake and in a peculiarly favorable condition for observation, at rest, lying down, etc.

4. Feeble shock, perceptible to persons awake and moving about; capable of waking persons who are asleep; making suspended objects or liquids oscillate.

5. Shock of moderate intensity, displacing movable objects.

6. Rather strong shock, upsetting furniture, making fissures in the walls and ceilings of houses.

7. Strong shock, damage to houses, chimneys thrown down.
8. Very strong shock, outhouses and huts thrown down.
9. Extremely strong shock, well-built houses thrown down.
10. Shock of extreme intensity, disturbance of strata, fissures in the earth's crust, rock-falls from mountains.

(10) *Mercalli Scale. I.*

"Vulcani e Fenomeni Vulcanici in Italia" (Parte III of Negri, Stoppani and Mercalli's "Geologia d'Italia"), pp. 217-218. 1883.

This is merely an adaptation of the de Rossi scale (No. 8), and is used in Mercalli's catalogue of Italian earthquakes given in the work mentioned above. It bears a close resemblance to the Saderra Masò and Rockwood scales (Nos. 7 and 13). I have prefixed the numbers 1 to 6 to the different degrees of this scale. The numbers in parentheses are the corresponding numbers of the de Rossi scale as given by Mercalli.

1. Slight, felt without the aid of seismographs by a few or many persons, but not universally (2, 3).
2. Moderate, with general shaking of fastenings, chandelier-prisms, etc., and ringing of some bells (4, 5).
3. Strong, more or less general ringing of bells, stopping of clocks, and oscillation of lamps (6).
4. Very strong, fall of plaster and of some chimneys; cracks in buildings, ringing of church bells (7, 8).
5. Ruinous, total or partial fall of some buildings (9).
6. Disastrous, ruins of many buildings, loss of life (10).

(11) *Rossi-Forel Scale.*

Bullettino del Vulcanismo Italiano, anno 10, 1883, pp. 67-68; *Archives des Sciences Physiques et Naturelle*, 11, 148-149. 1884.

Soon after the publication of the Forel scale, Professor Forel and Professor de Rossi each became acquainted with the scale suggested by the other. Both scales contained points worth preserving, and, on the invitation of de Rossi, the two seismologists met in order to agree on a single scale for the earthquakes that occurred on both sides of the Alps. Their success was probably greater than they anticipated, for the resulting scale has been more widely used than any other. Though it no doubt has several defects, it would be difficult, I think, to over-estimate the value of the results which have followed from its use.

It should be noticed that the scale given below is translated from the Swiss version, which is much the more widely known. In the *Bullettino del Vulcanismo Italiano*, anno 10, 1883, pp. 67-68, de Rossi states that the changes were drawn up in agreement with the Swiss Seismological Commission.⁵ The two versions, Italian and Swiss, are given in parallel columns; and it is curious to note that, while there is really no fundamental difference between them, there are several variations in points of detail. On the whole, the Italian version approximates more closely to the last form of the de Rossi scale (1878) than to the Swiss version of the combined scale.⁶ For instance, the Italian version retains the following ineffective tests, "announced in the newspapers or by those who are not seismologists" (degree III), and "some persons say that fortunately no damage occurred" (degree VI). The Swiss version no doubt owes its wider circulation to its publication in the French language and in a more readily accessible journal; but, even if it had been otherwise, there can be little doubt that it is the superior form.

- I. Recorded by a single seismograph, or by some seismographs of the same pattern, but not by several seismographs of different kinds; the shock felt by an experienced observer.
- II. Recorded by seismographs of different kinds; felt by a small number of persons at rest.
- III. Felt by several persons at rest; strong enough for the duration or direction to be appreciable.
- IV. Felt by several persons in motion; disturbance of movable objects, doors, windows; creaking of floors.
- V. Felt generally by everyone; disturbance of furniture and beds; ringing of some bells.
- VI. General awakening of those asleep; general ringing of bells; oscillation of chandeliers, stopping of clocks; visible disturbance of trees and shrubs; some startled persons leave their dwellings.
- VII. Overthrow of movable objects, fall of plaster, ringing of church bells, general panic, without damage to buildings.
- VIII. Fall of chimneys, cracks in the walls of buildings.

⁵ "Cette échelle déduite des effets produits par une secousse, vient être complétée d'accord avec la Commission Suisse de sismologie."

⁶ In a subsequent volume of the *Bullettino* (anno 12, p. 8, 1885), the Italian version is repeated.

IX. Partial or total destruction of some buildings.

X. Great disasters, ruins, disturbance of strata, fissures in the earth's crust, rock-falls from mountains.

(12) *Johnston-Lavis Scale.*

"Monograph of the Earthquakes of Ischia," pp. 75-79 and plates 3, 4. 1885

Dr. H. J. Johnston-Lavis, in his investigation of the Ischian earthquakes of 1881 and 1883, used the following scale in order to investigate the distribution of damage within the very small area of destruction. The wording of the tests is not absolutely identical in the accounts of the isoseismal lines of the two earthquakes and in the maps of the same. I have given the later version. It will be seen that the scale closely resembles Mallet's first scale (No. 4).

1. Buildings completely destroyed.
2. Buildings partially destroyed or damage to them very marked.
3. Buildings severely fissured or distinctly injured.

(13) *Rockwood Scale.*

American Journal of Science, 32, 7-8. 1886.

This scale resembles the Saderra Masò scale in consisting of adjectives only with their corresponding expression in terms of the Rossi-Forèl scale. The only difference between the two scales lies, indeed, in the division between the third and fourth degrees.

1. Very slight (II, III).
2. Light (IV).
3. Moderate (V, VI).
4. Strong (VI, VII).
5. Severe (VIII).
6. Destructive (IX, X).

(14) *Holden Scale.*

American Journal of Science, 35, 428-429. 1888.

In 1887, Professor E. S. Holden published his valuable catalogue of Californian earthquakes. Subsequently, he endeavored to obtain an estimate of the absolute value of the earthquake intensity developed in San Francisco during the historic period of the State. The Rossi-Forèl scale being unsuitable for the purpose, he estimated the mechanical equivalent of all the degrees of the scale except the highest. His estimate was based on the amplitude and period of the principal vibrations of Japanese earthquakes registered by Ewing, Milne, and Sekiya. For twenty-one earthquakes, for which these elements were measured, the description of the effects of the shock on buildings is so detailed that

the intensity can be assigned in terms of the Rossi-Forel scale as far as the ninth degree. The intensity corresponding to each degree is given below as measured by the maximum acceleration in millimeters per second per second. Though Professor Holden's object was a somewhat limited one, it is evident, I think, that he should be regarded as the first seismologist to devise an absolute or dynamical scale of seismic intensity. His claim in this respect does not seem to be lessened by the fact that his scale is a mere translation into precise terms of an imperfect arbitrary scale; for, like other arbitrary scales (Nos. 21 and 26), it implies the use of accurately constructed instruments.

Degree of the Rossi-Forel Scale	Max. accel. in mm. per sec. per sec.
I.	20
II.	40
III.	60
IV.	80
V.	110
VI.	150
VII.	300
VIII.	500
IX.	1200

(15) *Davison Scale.*

③ *Philosophical Magazine*, 50. 51. 1900.

This scale, first used in studying British earthquakes in 1889, differs from the Rossi-Forel scale in the inclusion of but one test to each degree. Degrees 8 and 9 correspond to degree VIII of the Rossi-Forel scale. As violent earthquakes never visit Great Britain, degrees corresponding to degrees IX and X of the Rossi-Forel scale are not required. Owing to the restriction to a single test for each degree, the isoseismal lines can be drawn with much greater accuracy; but, for the same reason, the scale is of little use in thinly populated countries.

1. Recorded only by instruments.
2. Felt only by a few persons lying down and sensitive to weak tremors.
3. Felt by ordinary persons at rest; not strong enough to disturb loose objects.
4. Windows, doors, fire-irons, etc., made to rattle.
5. The observer's seat perceptibly raised or moved.

6. Chandeliers, pictures, etc., made to swing.
7. Ornaments, vases, etc., overthrown.
8. Chimneys thrown down and cracks made in the walls of some, but not many, houses in one place.
9. Chimneys thrown down and cracks made in the walls of about one-half the houses in one place.⁷

② (16) *Baratta Scale*.

Annali dell'Ufficio Meteorologico e Geodinamico, 11, 19. 1892.

This scale was devised by Dr. M. Baratta, the well-known historian of Italian earthquakes for use in his investigation of the Verona earthquake of June 7, 1891. It resembles the preceding scale in being an obvious modification of the Rossi-Forel scale.

1. Very slight, noted by instruments only.
2. Slight, felt by a few persons without the aid of instruments.
3. Moderate, accompanied by general shaking of fastenings, crystals, etc.
4. Strong, with more or less general ringing of bells, stopping of clocks, oscillation of lamps.
5. Very strong, with fall of plaster and of a few chimney-pots, cracks in buildings, ringing of bells.
6. Almost ruinous, with total or a partial fall of a few (one or two) buildings.
7. Ruinous; ruin of several buildings, a little loss of life.

(17) *Japanese Scale*.

"Report on Earthquake Observations in Japan, 1892," p. 10; *Earthquake Investigation Committee Publication in Foreign Languages*, no. 4, p. 140. 1900.

The first form of this scale (1892) contains only three degrees, and is obviously unsuited for detailed inquiries. The corresponding degrees of the Rossi-Forel scale are added in parentheses.

1. Slight, just sufficient to be felt (I, II).

⁷ With later experience, I should be disposed to modify the first three degrees as follows:

1. Recorded by instruments adjusted to respond to rapid vibrations only.
2. Felt only on the upper floors of houses, but not strongly enough to make doors, windows, etc., rattle.
3. Felt on the ground-floors of houses, but not strongly enough to make doors, windows, etc., rattle.

2. Weak, the motion distinctly felt, but not so violent as to be necessary for people to run out of doors (III-V).

3. Strong, when most people run out of doors, some pieces of furniture are overturned, liquids thrown out, buildings damaged, the ground cracked or rent (VI-X).

In the later form of the scale (1900), the third degree is subdivided into the following degrees:

3. Strong (VI, VII).

4. Violent (VIII-X).

(18) *Ricco Scale.*

(2) *Annali dell'Ufficio Centr. di Meteorologico e Geodinamico*, 15, part 1, p. 3. 1893.

The following scale was devised by Professor A. Ricco for the construction of the isoseismal lines of the Etnean earthquake of April 22, 1893. In all the earthquakes of the Etnean region, the intensity declines very rapidly outwards from the epicenter, and the isoseismal lines are in consequence closely packed. For such earthquakes, a scale with few degrees is ample. In his map of a later Etnean earthquake (that of Fondo Macchia on October 15, 1911), Professor Ricco used the Mercalli scale (No. 19), but only five degrees of it, namely, 2, 4, 6, 8, and 10 (*Boll. Soc. Sism. Ital.*, 16, 27, 1912).

1. Shock indicated by seismic instruments only.

2. Shock felt by persons.

3. Shock felt by persons with alarm.

4. Shock which produced damage in some houses.

5. Shock which produced serious damage in many houses.

6. Shock which produced the fall of houses.

(19) *Mercalli Scale. II.*

Ital. Sism. Soc. Ital., 8, 184-191. 1902.

The second Mercalli scale (which will be called in future the Mercalli scale) is a modification of the Rossi-Forel scale, and, for a country visited by strong earthquakes, is an improvement. As it is specially adapted for the study of Italian earthquakes, it is now adopted as the standard of the Central Office of Meteorology and Geodynamics at Rome. Its chief defect is the increased number of tests in each degree of the scale. I have added to each degree the equivalent degree of the Rossi-Forel scale, as given by Professor Mercalli.

1. Instrumental shock, that is, noted by seismic instruments only (I).

2. Very slight, felt by several persons, but by few relatively to the number of inhabitants in a given place; said by them to have been *hardly felt*, without causing any alarm, and in general without their recognizing it as an earthquake until it was known that others had also felt it (III).

3. Sensible or moderate, not felt generally, but felt by many persons indoors, though by few on the ground floor, without causing any alarm, but with shaking of fastenings, crystals, creaking of floors, and slight oscillation of suspended objects (IV-V).

4. Rather strong, felt generally indoors, but by few outside, with waking of those asleep, with alarm of some persons, rattling of doors, ringing of bells, rather large oscillation of suspended objects, stopping of clocks (VI).

5. Strong, felt by everyone indoors, and by many with alarm and flight into the open air; fall of objects in houses, fall of plaster, with some cracks in badly built houses (VII).

6. Very strong, felt with general alarm and flight from houses, sensible also out of doors; ringing of church bells, fall of chimney-pots and tiles; cracks in numerous buildings, but generally slight (VIII).

7. Ruinous, felt with great alarm, partial ruin of some houses, and frequent and considerable cracks in others; without loss of life, or only with a few cases of personal injury (IX).

8. Disastrous, with complete or nearly complete ruin of some houses and serious cracks in many others, so as to render them uninhabitable; a few lives lost in different parts of populous places (X).

9. Very disastrous, with ruin of many buildings and great loss of life, cracks in the ground, landslips from mountains, etc. (greater than X).

(20) *Oldham Scale.*

Memoirs Geological Survey of India, 29, 42-43. 1899.

This scale was adopted by Mr. R. D. Oldham in his valuable investigation of the great Indian earthquake of 1877. To a great extent, the epicentral area of this earthquake is "a wild, thinly populated country, and even in the thickly populated parts, brick and stone buildings are rare and widely scattered." * The Oldham scale thus contains only

* This scale has been used by Dr. M. Stuart in his investigation of the Srimangal earthquake of July 8, 1918. *Records Geological Survey of India*, 49, 173-189. 1918.

six degrees, three of which are applicable only to the area of destruction.

1. The destruction of brick and stone buildings practically universal.
2. The damage to masonry or brick buildings universal and often serious, amounting in some cases to destruction.
3. All, or nearly all, brick buildings damaged.
4. The earthquake universally felt, severe enough to disturb furniture and loose objects, but not to cause damage (except in a few instances) to brick buildings.
5. The earthquake smart enough to be generally noticed, but not severe enough to cause any damage.
6. The earthquake only noticed by a small proportion of people who happened to be sensitive, and, being seated or lying down, were favorably situated for observing it.

(21) *Omori Scale.*

Earthquake Investigation Committee Publication in Foreign Languages, no. 4, pp. 14 and 137-141. 1900.

In his investigation of the Mino-Owari earthquake of 1891, Professor Omori estimated the intensity of the earthquake-motion from measurements of many stone-lanterns, tombstones, etc. The following absolute or dynamic scale, expressing the relation between the maximum acceleration so determined and the damage wrought by the shock, is deduced chiefly from the observations on the effects of this earthquake. The movement is supposed to be entirely horizontal, and, in the neighborhood of the epicenter, corrections in the figures given, amounting to as much as 200 mm. per second per second might be necessary. As will be seen, the scale is devised for the measurement of destructive shocks and especially for the earthquakes of Japan.

Under each heading, several equivalent effects of the shock are given, clearly with the object of facilitating the application of the scale. Professor Omori does not explain how the equivalence of these effects was determined. I imagine, however, that isoseismal lines corresponding to the various intensities (300, 900, 1200, etc., mm. per sec. per sec.) were drawn, and that the corresponding effects were noticed within, but not outside, each isoseismal so drawn. If this is the case, the tests under any degree of the scale would correspond to an intensity of that degree or to one between that degree and the next above it; and thus the line enclosing any two or three places at which different tests for

the same degree are satisfied need not be an isoseismal line. To attain accuracy, the construction of isoseismal lines by the employment of so many tests must require a large number of observations.

1. Maximum acceleration 300 mm. per second per second. The motion strong enough to make people generally run out of doors; badly built brick walls slightly cracked; plaster of some old *dozo* (godowns) shaken down; furniture overthrown; wooden houses so much shaken that cracking noises are produced; trees visibly shaken; waters in ponds rendered slightly turbid owing to the disturbance of the mud; pendulum clocks stopped; a few factory chimneys of very bad construction damaged (VII).

2. Maximum acceleration 900 mm. per second per second. Walls in Japanese houses cracked; old wooden houses thrown slightly out of the vertical; badly constructed tombstones and stone-lanterns overturned; in a few cases, changes in hot springs and mineral waters; ordinary factory chimneys not damaged.

3. Maximum acceleration 1200 mm. per second per second. About one factory chimney in four damaged; badly built brick houses partially or totally destroyed; a few old wooden dwelling houses and warehouses totally destroyed; wooden bridges slightly damaged; some tombstones and stone-lanterns overturned; *shoji* (Japanese paper-covered sliding doors) broken; roof-tiles of wooden houses disturbed; some rock fragments thrown down from mountain sides (VIII).

4. Maximum acceleration 2000 mm. per second per second. All factory chimneys broken; most ordinary brick buildings partially or wholly destroyed; some wooden houses totally destroyed; wooden sliding doors and *shoji* mostly thrown out of the grooves; cracks two or three inches wide in low soft ground; embankments slightly damaged here and there; wooden bridges partially destroyed; ordinary stone-lanterns overturned (IX).

5. Maximum acceleration 2,500 mm. per second per second. All ordinary brick houses very severely damaged; about three per cent of the wooden houses totally destroyed; a few *tera* (Buddhist temples) thrown down; embankments severely damaged; railway lines slightly curved or contorted; ordinary tombstones overturned; masonry walls damaged here and there; cracks one or two feet wide along river banks; water in rivers and ditches thrown over the banks; changes in the waters of most wells; landslips (X).

6. Maximum acceleration 4,000 mm. per second per second. Most *tera* thrown down; 50 to 80 per cent of the wooden houses totally de-

stroyed; embankments shattered almost to pieces; roads through paddy fields so much cracked and depressed as to stop the passage of wagons and horses; railway lines very much contorted; large iron bridges destroyed; wooden bridges partially or totally damaged; tombstones of stable construction overturned; cracks a few feet wide in the ground, accompanied sometimes by the ejection of water and sand; earthenware buried in the ground mostly broken; low ground, such as paddy fields, very much convulsed both horizontally and vertically, sometimes killing trees and vegetation; numerous landslips.

7. Maximum acceleration much more than 4,000 mm. per second per second. All buildings, except a very few wooden houses, totally destroyed; some houses, gates, etc., projected from one to three feet; remarkable landslips, accompanied by faults and shears of the ground.

(22) *Cancani Scale.*

Verhandlungen der zweite internationalen seismologischen Konferenz (1904).⁹

The absolute scale of Professor Omori is designed for destructive shocks alone. A somewhat similar scale applicable to shocks of all degrees of strength is that suggested by the late Dr. A. Cancani. It consists of the following twelve degrees:

Degree	Max. accel. in mm. per sec. per sec.
1. Instrumental	0-2.5
2. Very slight	2.5-5
3. Slight	5-10
4. Sensible or moderate	10-25
5. Rather strong	25-50
6. Strong	50-100
7. Very strong	100-250
8. Ruinous	250-500
9. Disastrous	500-1000
10. Very disastrous	1000-2500
11. Catastrophe	2500-5000
12. Enormous catastrophe	5000-10000

⁹ I regret that I am unable to quote this scale from the original paper. At the time of its publication, Great Britain had not joined the International Seismological Association, and, so far as I know, there is not a copy of this volume of the *Verhandlungen* in the country.

(23) *Wood Scale.*

"The Californian Earthquake of April 18, 1906: Report of the State Earthquake Investigation Commission," 1, pt. 1, 224-225. 1908.

The Wood or San Francisco scale was planned by Mr. H. O. Wood in his investigation of the distribution of apparent intensity in San Francisco caused by the Californian earthquake of April 18, 1906. The scale consists of five degrees, in which I have substituted numbers for the letters which Mr. Wood uses. It is, as Mr. Wood says, "simply a classification of the phenomena observed. It defines as many grades as the facts seemed to express in this field. It is more finely subdivided than the Rossi-Forel scale and, for conditions in a modern city, the definitions are better framed."

1. Very violent. Comprises the rending and shearing of rock masses, earth, turf, and all structures along the line of faulting; the fall of rock from mountain sides; numerous landslips of great magnitude; consistent, deep, and extended fissuring in natural earth; some structures totally destroyed.

2. Violent. Comprises fairly general collapse of brick and frame buildings when not unusually strong; serious cracking of brick work and masonry in excellent structures; the formation of fissures, step-faults, sharp compression anticlines, and broad, wave-like folds in paved and asphalt-coated streets, accompanied by the ragged fissuring of asphalt; the destruction of foundation walls and underpinning structures by the undulation of the ground; the breaking of sewers and water-mains; the lateral displacement of streets; and the compression, distention, and lateral waving or displacement of well-ballasted street-car tracks.

3. Very strong. Comprises brick work and masonry badly cracked, with occasional collapse; some brick and masonry gables thrown down; frame buildings lurching or listed on fair or weak underpinning structures, with occasional falling from underpinning or collapse; general destruction of chimneys and of masonry, brick or cement veneers; considerable cracking or crushing of foundation walls.

4. Strong. Comprises general but not universal fall of chimneys; cracks in masonry and brick work; cracks in foundation walls, retaining walls, and curbing; a few isolated cases of lurching or listing of frame buildings built upon weak underpinning structures.

5. Weak. Comprises occasional fall of chimneys and damage to plaster, partitions, plumbing, and the like.

The corresponding accelerations in millimeters per second per second, as given by Mr. Wood, are more than 3000, 1200-3000, 800-1200, 200-800, less than 200.

(24) *Milne Scale.*

British Association Report, 1911.

In his great "Catalogue of Destructive Earthquakes," the late Professor Milne indicated the intensity of the earthquakes by means of a scale consisting of three degrees. The corresponding accelerations in millimeters per second per second is added in parentheses. The scale bears a close resemblance to the Johnston-Lavis scale (No. 12).

1. Walls cracked, chimneys broken, old buildings shattered, slight cracks produced in the ground; radius of destruction not more than five miles (1000).

2. Buildings unroofed or shattered, some buildings fallen, the ground badly cracked in places, small landslips; radius of area of destruction twenty miles (1500).

3. Towns destroyed and districts devastated; ground faulted and fissured, water, mud, and sand issuing from the openings; landslips common in hilly countries; radius of area of destruction one hundred miles (3000, or more than 3000).

(25) *Sieberg Scale.*

Gerland's Beiträge zur Geophysik, 11, 227-239. 1912.

Sieberg's scale is an expansion of the well-known Mercalli scale (No. 18), the chief differences being: (1) the recognition that the seismometers referred to in the lowest degree must be adapted to register rapid vibrations; (2) the increased number and definiteness of the tests in each degree; (3) the attempt to take into account the varying strength of houses in different countries; and (4) the division of the highest degree of the Mercalli scale into three degrees. Most of these changes seem to me improvements. The chief defects of the scale are its extreme complexity, the great number of tests in all but the lowest degrees, and the doubt whether all the tests of any one of the higher degrees correspond to equal intensities of the shock. If these tests were absolutely equivalent, the scale would be admirably adapted for the comparison of the intensities of earthquakes in different countries. A minor defect is the appeal to different degrees of alarm referred to in degrees 4, 5, and 6.

1. Imperceptible. The shock is not felt by man; only the records of seismometers adapted for earthquakes of near origin, or of sensitive seismoscopes give notice of it.

2. Very slight. Only a few persons in perfect repose, especially those with sensitive nerves, feel the shock as a slight tremor or rocking. The shock is especially sensible on the upper floors of houses and very rarely on the ground floor. Also, the quiet of the night is favorable to its perception, if the observer is awake.

3. Slight. Even in densely populated districts, the shock is felt by only a few persons as a shaking like that produced by the rapid passing of a wagon. Occasionally, the duration, and perhaps also the direction, of the movement can be detected. Many only realize afterwards, in talking with others, that there has been an earthquake.

4. Moderate. Of persons in the open air, not many feel the earthquake. Indoors, many persons, but not all, recognize the trembling or slight rocking movement of furniture; glasses and crockery near together gently strike one another as they do when a heavily laden wagon is driven by on an uneven pavement; windows rattle; doors, joists, floors, and ceilings creak; liquids in open vessels are slightly moved. Alarm is hardly ever caused except in the case of persons who have already become nervous and anxious through the experience of other earthquakes. In a few cases, sleepers awake.

5. Rather strong. Even during the busiest hours of the day, the earthquake is felt by many persons in the open air. Indoors, the shaking of the whole building is generally noticed, the feeling being the same as when some heavy object (such as a sack or piece of furniture) falls in the house; or the observers move, together with chair, bed, etc., as in a ship on an agitated sea. Plants, the branches and weaker boughs of shrubs and trees sway visibly, as they do with a moderate wind. Freely hanging objects, such as curtains and lamps, but not heavy chandeliers, oscillate; small bells ring; the pendulums of clocks are stopped or swing more widely according as the direction of the shock is at right angles or parallel to the plane of oscillation; similarly, stopped pendulum clocks are set going; the striking spring of clocks sounds; electric lights fail to act when contact of the conducting wire is made; pictures rattle against the walls or are displaced; small quantities of liquid are spilt out of well-filled open vessels; ornaments, small standing frames fall and also objects leaning against the wall; even light furniture may be somewhat shifted from its place, rattling of furniture; doors and window-shutters open or shut; window-panes crack. Sleepers as a rule are awakened. A few persons run into the open air.

6. Strong. The earthquake is felt by everyone with alarm, so that very many persons run into the open air, many thinking that they must

fall. Liquids move violently, pictures fall from the walls, books, etc., from shelves, unless the direction of the shock is parallel to that of the walls; numerous vessels are broken; a few pieces of stable furniture are shifted or overturned; church bells and church clocks strike. In a few solidly built mid-European houses there are cracks in the plaster, which is detached here and there in fragments from the roof and walls. In poorly built houses, the damage is greater, but still not of a serious nature.

7. Very strong. Considerable damage is done to furniture through the upsetting or breaking even of heavy pieces. Even large church bells strike. The surfaces of rivers, ponds, and lakes are disturbed, and the mud at the bottom stirred up. A few slips of sandy and gravelly coasts. The level of water in wells is changed. Notwithstanding their solid construction, many mid-European houses suffer moderate damage; there are slight fractures in walls, large pieces of plaster crumble down, tiles fall, pantiles are loosened and slip down. Chimneys are damaged by cracks and by the falling of weather moulding and stones; chimneys in bad condition break off at the roof and injure it. Badly fastened decorations fall down from towers and high buildings. In framework buildings, and especially in their partition walls, the damage to the plastering is great. Buildings that are badly built or out of repair suffer seriously in the same way; wooden fences, sheds, high enclosure walls, cottages and even churches, minarets of mosques, etc., in many country districts of southern Europe, fall down to a greater or less extent. Earthquake-proof buildings, such as most of the stone and wooden houses in Japan, and the wood and wattled buildings, which are used in such great quantities in tropical earthquake-districts, remain quite undamaged.

8. Ruinous. The trunks of trees, of palms especially, sway as with a strong wind. Even the heaviest pieces of furniture are shifted some distance or overturned. Statues, etc., near the ground, such as those in churches, churchyards, public parks, etc., either rotate on their pedestals or fall. Stone enclosure-walls are split and thrown to the ground. Notwithstanding their solid construction, mid-European houses suffer serious damage, with gaping cracks in the masonry; in some cases, they collapse partly; most chimneys fall; church towers and factory chimneys especially so suffer, and, by their fall, neighboring houses may be more seriously damaged as if by the action of the shock alone; exceptionally well-built factory chimneys are only fractured and displaced in their upper portions. Earthquake-proof buildings (such

as those of Japan) show slight damage, such as fractures, the crumbling of plaster, etc. (see degree 7, mid-European houses), and wooden houses crack considerably in their joints. Rotten posts of Malayan stake-huts break. Slight cracks in the ground near steep slopes and in damp soil; a few outflows of water carrying small quantities of sand or mud.

9. Disastrous. Solidly built houses of European construction are seriously damaged, so that a large number becomes uninhabitable, a few fall completely or nearly so. Framework buildings are displaced on their stone foundations, on account of which they are under certain conditions damaged. Earthquake-proof buildings made of stone show considerable damage, the walls of wooden ones reveal gaps and cracks, old wooden houses are loosened in their frames.

10. Destructive. Most stone and framework buildings are overthrown together with their foundations, even first-class brick walls show dangerous cracks, but the percentage of those of mid-European construction is larger than in the case of earthquake-proof buildings. Even well-built wooden houses and bridges suffer serious damage, a few are even demolished. Embankments, dams, etc., are more or less considerably damaged. Iron railway-lines are slightly bent. Conduit pipes (gas, water, etc.) in the ground are rent or compressed. Fissures and undulating folds are formed in the asphalt of the streets. Loose, and especially damp, ground shows fissures up to several decimeters in width; especially near water-courses, there may be parallel fissures from one-half to three-quarters of a meter wide. Not only does loose ground slide down from cliffs as landslips, but also rock-slides fall into the valleys from the mountains, from the banks of rivers and even steep coasts whole parts break off, and on flat coasts masses of sand and mud are displaced, by which substantial changes in the form of the ground are wrought. The level of water springs is changed. From rivers, canals and lakes, water is thrown on to the banks.

11. Catastrophe. Stone buildings of whatever kind practically no longer stand. Even solid buildings of wood or wattling are only in a few cases able to survive, especially near lines of faulting. Bridge-buildings, though large and securely constructed, are destroyed by the breaking off of massive stone piers or fracture of iron shafts. Yielding wooden floors, however, are sometimes less damaged. Embankments and dams are quite torn asunder, frequently for long distances. Iron rails are strongly bent and compressed. The kind and amount of dam-

age to roads depends on the nature of the foundations. Conduit pipes in the ground are completely severed and rendered useless. The most varied and very considerable morphological changes of the ground are noticed, which are closely defined by the nature of the ground; wide fissures and cracks are formed, the derangements in the horizontal and vertical directions being specially important in soft and watery ground. There is also the appearance in various forms of water carrying sand and mud. Landslips and rocks-falls are numerous.

12. Great catastrophe. No work of human hands remains standing. The derangements and transformations of the ground attain the grandest dimensions. Even in rocky ground, faults of considerable depth are formed, with great horizontal movements and numerous fissures. Rock cliffs break, rock-falls, landslips, collapse of river banks or shore are numerous and widespread. Underground and surface waters in consequence undergo the most various derangements; waterfalls are formed, lakes are dammed, rivers diverted, etc.

(26) *McAdie Scale.*

Bulletin of the Seismological Society of America, 5, 123. 1915.

In his presidential address in 1915 to the Seismological Society of America, Mr. McAdie proposed an absolute scale, which, it will be seen, differs only from Cancani's by including the first three degrees of that scale in one. This would seem to be an improvement, since, according to Professor Omori, the maximum acceleration of a just perceptible shock is 17 mm. per sec. per sec.

Degree	Accel. in mm. per sec. per sec.
1. Instrumental	1-10
2. Feeble	10-25
3. Slight	25-50
4. Moderate	50-100
5. Some damage	100-250
6. Strong	250-500
7. Much damage	500-1000
8. Disastrous	1000-2500
9. Catastrophic	2500-5000
10. Absolute ruin	5000-10000

(27) *Reid-Taber Scale.*

"The Porto Rico earthquake of 1918: Report of the Earthquake Investigation Commission," by H. F. Reid and S. Taber, p. 9. Washington, 1919.

In their investigation of the severe Porto Rico earthquake of 1918, Messrs. Reid and Taber found it necessary to modify the Rossi-Forel scale, in order to suit the local conditions of the island. The mampos-teria buildings referred to are built chiefly of stones placed in lime mortar which is so weak that it will readily crumble to pieces between the fingers.

1. Shock recorded by seismographs.
2. Felt by a very few persons at rest or favorably situated.
3. Felt by many persons at rest or favorably situated.
4. Felt by persons walking. Movement or rattling of doors, windows, shutters, etc.
5. Felt by nearly everyone. Furniture moved.
6. General awakening of those asleep, ringing of bells; stopping of pendulum clocks. Bushes and trees visibly agitated. Small cracks in a few mampos-teria buildings of poor construction and poor mortar. Overthrow of a few relatively unstable objects.
7. Overthrow of many movable objects, such as vases, bottles, etc. Fall of plaster in many buildings. Some walls of mampos-teria badly cracked. Cracks in mortar of some buildings of brick, stone, or concrete blocks.
8. Many mampos-teria walls badly shattered; some walls partly or wholly thrown down. Small cracks in some concrete buildings.
9. General destruction of mampos-teria buildings. Cracks pass through bricks and concrete blocks where mortar is strong. Cracks in many concrete buildings, and some concrete walls thrown down.
10. General destruction of all buildings except those specially adapted to resist earthquake shock. Some trees are broken and up-rooted.

GENERAL REMARKS ON THE ABOVE SCALES

Of the above scales, some are used merely to express the relative intensity of different members of a series of earthquakes (Nos. 1, 3, 4, 6, 13, and 24); the remainder were devised for the additional purpose of drawing isoseismal lines of an earthquake. A few have been used only once or twice for the latter purpose (Nos. 2, 5, 16, 18, and 20). Though most of the scales are applicable to earthquakes of all degrees of intensity, three (Nos. 2, 3, and 15) refer to earthquakes of slight to moderately destructive intensity; while six others (Nos. 4, 5, 12, 20, 23, and 24) are only chiefly useful for destructive earthquakes.

A more important mode of classifying the scales is that according to their nature. They may be grouped in three divisions:

(a) *Personal scales.* The Macfarlane and Williamson scales (Nos. 3 and 6) are the simplest examples of a personal scale. In its first conception, the Saderra Masò scale (No. 7), and possibly also the Rockwood scale (No. 13), would fall under this heading. Their subsequent expression in terms of the Rossi-Forel scale transfers them, however, to the second division.

(b) *Arbitrary scales.* This class includes by far the greater number of the scales. In all of them the degrees correspond to successive stages of intensity. They are arbitrary in so far as there is no definite series of intervals between the intensities corresponding to successive degrees. And, to a certain extent, they are wanting in precision, for the same test might correspond to different degrees in different countries.

(c) *Absolute scales.* Under this heading are included the scales of Holden, Omori, Cancani, and McAdie (Nos. 14, 21, 22, 26). In all these scales, it is essential that the maximum acceleration should be determined instrumentally and not by translating the intensity in terms of an arbitrary scale into its estimated equivalents in terms of an absolute scale.

It will be admitted that personal scales are valueless except in so far as they furnish a rough means of indicating the order of intensity of a number of shocks observed by the same person. Such scales are now definitely abandoned by seismologists, and none would suggest their revival.

The choice thus lies between arbitrary and absolute scales. If they were both applicable with equal ease, there can be no doubt that some absolute scale would carry the day, and it would be a simple matter for seismologists to agree to the use of some particular scale all over the world.¹⁰ But the difficulties in the way of an absolute scale would seem at present to be insuperable, namely, the want of absolute accuracy in our present seismographs and the impossibility of providing them in sufficient numbers to be of any service. Thus, while we may look forward with confidence to the ultimate removal of these difficulties, we are left with one of two alternatives, either to use an arbitrary scale or none at all.

¹⁰ It would, I think, be difficult to improve upon the McAdie Scale (no. 26), which, if it were adopted, should, I think, be known as the Cancani-McAdie scale.

The latter alternative has been suggested by a few writers. It is said that arbitrary scales, such as the Rossi-Forel and Mercalli scales, have outlived their usefulness (*Bulletin of the Seismological Society of America*, 5, 122, 1915), and that it is difficult to estimate the intensity by their means and therefore to draw isoseismal lines (*Ibid.* 6, 227-228, 1916).¹¹ I do not propose to consider these objections here, trusting rather that they will be met by the later sections of this paper.

THE INTENSITY AS DEPENDING ON THE POSITION OF THE OBSERVER

An observer's estimate of the intensity of a shock depends on his position and occupation at the time. If he is outside and walking, the apparent intensity is much less than if he is indoors and at rest. There are, moreover, fewer objects by the movement of which the intensity can be roughly measured. Speaking generally, the experience of a person who is out of doors is of little value in the construction of isoseismal lines.

Again, observers who are indoors and on the same floor may differ in their estimate of the intensity. And the impressions of the same person may vary if he should happen to alter his position during the shock. When the shock consists of two distinct parts of nearly equal strength, observers in the same place often differ in their views as to the relative intensity of the two parts. In many cases this may be due to defective memory; but it is so common that I can not help thinking that it is partly due to an observer's change of position after feeling the first part of the shock.

The position of the observer with respect to the ground floor of the house is probably of more importance. We might expect that the walls would to a certain extent vibrate like inverted pendulums, and therefore that the movement on an upper floor would be greater than

¹¹ It has also been urged (*Ibid.*, 6, 230, 1916) that the late Professor Milne never made use of an intensity scale (but see No. 24) and never drew an isoseismal line. But Professor Milne during his whole career investigated only one earthquake, that of February 22, 1880, in Japan. The de Rossi scale was in existence at that time, but was probably unknown outside Italy. The Rossi-Forel scale was not published until 1883. Moreover, Professor Milne only received 120 replies to his circulars, a number far too small for drawing the isoseismal lines of a strong earthquake. Compare with this the number of records obtained for some British earthquakes, e.g., 2902 for the Hereford earthquake of 1896, 1136 and 1467 for the Derby earthquakes of 1903 and 1904, 1428 for the Doncaster earthquake of 1905, 1168 for the Swansea earthquake of 1906, and 1241 for the Stafford earthquake of 1916.

that on the ground floor. This view is supported by the common observation that the persons who feel a shock near the boundary of the disturbed area are almost invariably on an upper floor of a house.

Professor Milne was the first to compare the range of motion on the ground floor and on an upper floor of a house.¹² The instruments he used were similar duplex pendulums (Ewing's), which give the range of motion but not its period. His experiments have been repeated by Professor Omori, who used horizontal pendulum seismographs, giving both elements of motion, in brick buildings of various types.¹³

Professor Omori described the buildings in which his experiments were made as, from a seismological point of view, very bad, ordinary, and good. In each case, the periods of vibration were approximately the same whether on the ground floor or on an upper floor. It was therefore sufficient to compare the ranges of motion at the different heights. In a very bad building, the range of the upper part of the wall was invariably greater than that at the ground level. In an ordinary building, the upper wall was shaken more strongly than the ground only in violent earthquakes or in earthquakes consisting of quick-period vibrations (less than half a second). In a good building, the upper wall and the ground have the same motion whatever be the strength of the shock.

Somewhat similar, but not identical, results are obtained from the study of British earthquakes. While investigating the last strong earthquake in England, the Stafford earthquake of January 14, 1916,¹⁴ I drew special attention to the floor of the house occupied by the observer at the time.¹⁵ The continuous lines in the sketch-map (Fig. 1) are isoseismal lines of intensities 7 to 3. These depend as usual on all observations, whether made on the ground floor or upstairs. Separating the observations made on the ground floor only, I drew from them a separate series of isoseismal lines of intensities 6 to 3, the observations of

¹² The movement produced in certain buildings by earthquakes. *Japan Seismological Society Transactions*, 12, 67-75. 1888.

¹³ Earthquake measurement in a brick building. *Earthquake Investigation Committee Publication in Foreign Languages*, no. 4, pp. 7-11, 1900; no. 12, pp. 57-65, 1902; no. 20, pp. 73-83, 1905.

¹⁴ *Geological Magazine*, 6, 302-312. 1919.

¹⁵ I may mention here that it was not desirable to ask this question in every case. Valuable information on the more important data can often be obtained by circulating brief lists of questions. The mere length of a list often deters observers from answering.

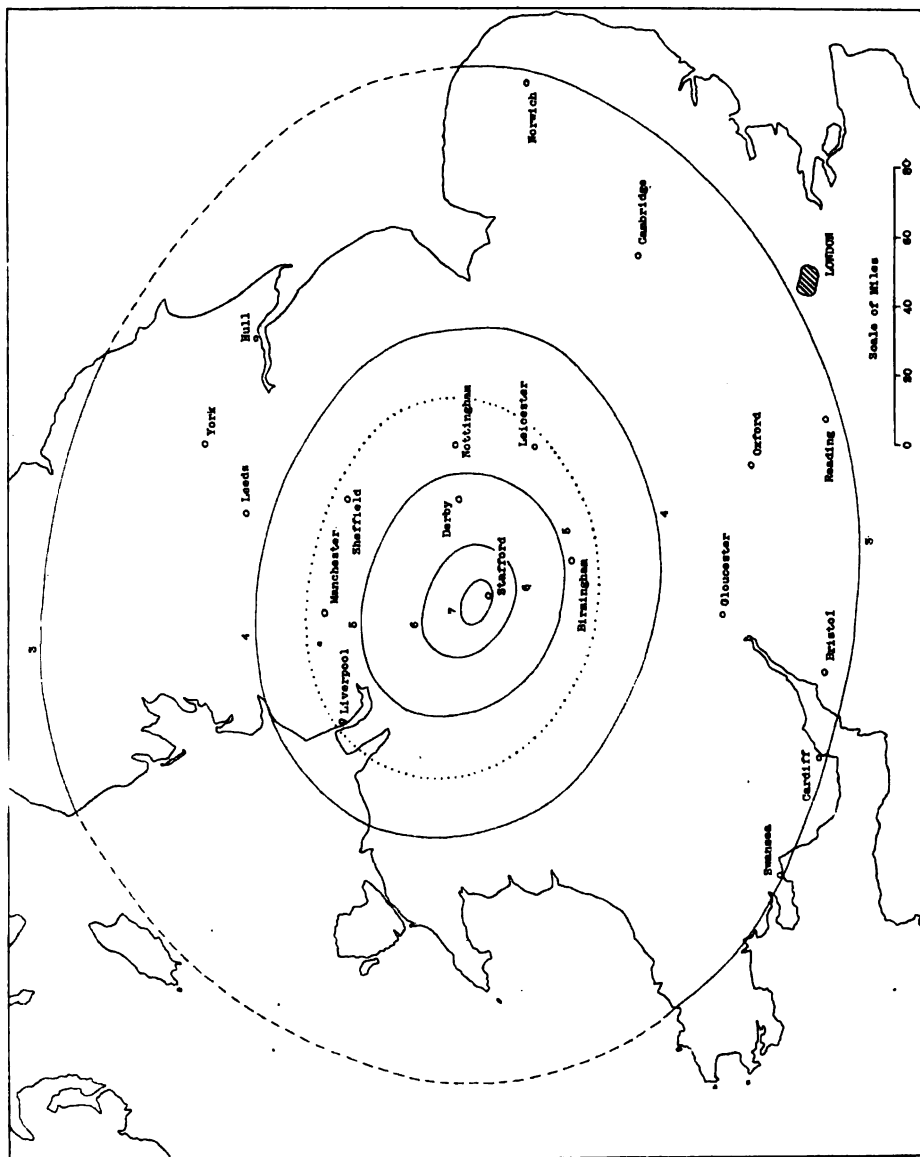


Fig. 1

intensity 7 being too few to determine the corresponding isoseismal, For intensities 6 and 5, the isoseismals on the two maps were practically coincident; but, for intensities 4 and 3, the isoseismals for the ground floor are much smaller than those for the whole series, of which the determining observations were evidently made on upper floors. The ground floor isoseismal 4 is represented by the dotted line. The corresponding curve for intensity 3 can not be drawn completely, but it lies a few miles outside the isoseismal 4 indicated by the continuous line. The areas included within these ground-floor isoseismals are respectively 6,570 and 16,000 or 17,000 square miles; those within the same isoseismals depending on all observations, being 12,500 and 50,200 square miles. Thus, when the shock is fairly strong, or perhaps I should say in the neighborhood of the epicenters, the intensities on the ground floor and on upper floors are practically the same; near the boundary of the disturbed area, a shock is felt more readily on an upper floor than on the ground floor.

In an earthquake as strong as the Stafford earthquake, the vibrations increase in period as they diverge from the origin. After traveling for eighty or a hundred miles, they become slow, gentle oscillations, something like those experienced in a carriage with good springs. It is possible that the period of these evanescent vibrations approaches that of the oscillations of the walls of an ordinary house, and they are therefore felt more strongly on the upper floors.

CONSTRUCTION OF ISOSEISMAL LINES

The value of isoseismal lines depends to a very great extent on the number of observations in each place and on the close distribution of the places. When an earthquake occurs in a sparsely populated country, or when the number of observations is small, any isoseismal lines that are drawn unavoidably present an appearance of precision which they do not in reality possess. It is quite possible, indeed it is probable, that they should be irregular; but again, unless the number of observations is very great, the irregularity of the curves suggests a distribution of intensity which may or may not be correct. Thus, unless the number of records at our disposal is considerable, it would seem desirable either to omit isoseismal lines altogether from our maps, or to depict them in some way (say, by dotted lines) to show that they are approximate, or to draw them on a very small scale map.

It is important that the intensity at any place should be determined, not by the observer, but by the investigator. Supposing the scale of

intensity No. 14 to be used, the experience of each observer would be given in answer to the following question:

Was the shock strong enough: (a) to make windows, doors, fire-irons, etc., rattle? (b) to cause the observer's seat to be perceptibly raised or moved? (c) to make chandeliers, pictures, etc., swing? (d) to overthrow ornaments, vases, etc.? (e) to throw down chimneys or make cracks in the walls of buildings?

The observer should also be asked to answer each part of the question as fully as possible and to give replies, whether positive or negative, to every part, negative evidence being of the greatest service in drawing isoseismal lines.

As an illustration of the method of determining the intensity at various places, I quote a few records from my map-analyses for the Stafford earthquake of January 14, 1916. A cross denotes an affirmative, and a cipher a negative, answer to the corresponding question above.

PLACE	INTENSITY			
	a	b	c	d
Hanley	0 + + 0	0 + + +	+ 0 + 0	0 0 0 0
	+ + + +	0 + + +	+ + + +	0 0 0 0
	+ + +	+		0 0
Marchington.....	+ + + +	+ + + +	+ 0 + +	0 0 0 0
Burslem	+ + + 0	+ + + 0	+ + 0	0 0 0
		+		
Brereton.....	+ + + +	+ + + +	+ 0	0 0
Wolverhampton.....	+ + + 0	+ + + +	0 0 0 +	0
	+ + + +	+ + + +	0	
	+ + + 0	+ + +		
Burton-on-Trent	+ + + +	+ 0 + +	0 0 0 0	0 0 0 0
	+ 0 + +	+ + + +	0 0	0 0 0
	+ + + +	0 + + +		
	+ 0	+ +		

From this table, we should infer that the intensity was 6 at Hanley and Marchington, probably 6 at Burslem, 6(?) at Brereton, and 5 at Wolverhampton and Burton-on-Trent. In constructing the isoseismal 6 all these observations would be useful, for the curve should include Hanley and Marchington, and probably Burslem; it should pass near Brereton, but whether excluding or including this village would depend

on the trend of the line in its neighborhood ; and it should exclude Wolverhampton and Burton-on-Trent.

In drawing isoseismal lines, it should be remembered that there may be many local variations of intensity which it is impossible in ordinary maps to represent. Within any given isoseismal line, there may be places at which the intensity apparently did not reach that corresponding to the isoseismal line. It may be that the intensity was really less than along the isoseismal line, or the defect may be only apparent and due to incomplete observation. On the other hand, outside the isoseismal line, there may be a few places at which the intensity was apparently equal to that along the line. The observation may point to a small outlier of higher intensity ; or it may be that some object happened to be in a position in which it was easily moved. Unless there were

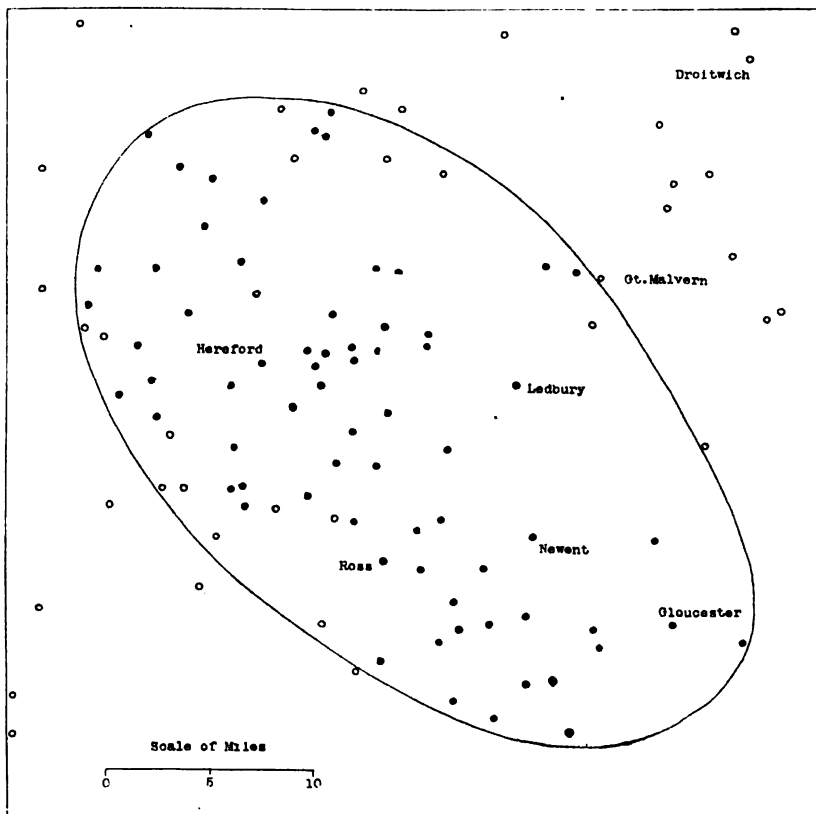


Fig. 2

many such observations in the immediate neighborhood, the isoseismal line obviously should not be deflected in consequence.

An example of the construction of isoseismal lines is given in Figure 2, which represents the isoseismal 8 of the Hereford earthquake of December 17, 1896.¹⁶ In this, the places at which damage occurred to buildings are indicated by dots, those at which there is no damage recorded by small circles. The line is drawn so as to include all the former places, and to exclude the latter as far as possible.

USE OF ISOSEISMAL LINES

In a great earthquake, the principal use of isoseismal lines is to depict the variation of intensity throughout the disturbed area. The position of the epicenter is usually rendered evident by the dislocation of the crust or the area of greatest destruction. In an earthquake of moderate strength, such as the strongest that we experience in Great Britain, accurately drawn isoseismal lines lead to results of equal significance, enabling us to determine the position of the epicenter, and the direction, hade, and approximate position of the fault in which the earthquake originated. In a paper on "The Investigation of Earthquakes,"¹⁷ I have explained these points in detail. It will be sufficient to state here that: (a) the epicenter is close to the center of the innermost isoseismal line; (b) the direction of the originating fault is parallel to that of the axes of the inner lines; (c) the fault hade toward that side on which the inner isoseismals are the farther apart; and (d) the fault-line lies a short distance from the epicenter on the side from which the fault hade.

One test of these methods is the extent to which the faults assigned by the seismic evidence agree in position with those known by careful geological surveys. It is not, however, an infallible test, unless the fault is a plane surface. If it should be a curved surface, the position given by the seismic conditions is the intersection with the ground of a tangent plane to the fault surface at the depth of the seismic focus. Thus, we should expect to find more close agreement between the seismically and geologically traced faults in countries in which the seismic foci are usually shallow than in those in which they are deeply seated.

Scotland and England are two such countries. In the Scottish earthquakes of intensity 7, the average area enclosed within the isoseismal 4 is less than a thousand square miles; in English earthquakes of the

¹⁶ "The Hereford Earthquake of December 17, 1896." Birmingham, 1899.

¹⁷ *Gerland's Beiträge zur Geophysik*, 9, 201-236. 1908.

same intensity, it is 22,000 square miles. For earthquakes of intensity 5, the corresponding areas are 450 and 780 square miles, and, in estimating the former figure, several earthquakes with very small areas are omitted. Thus, the intensity of Scottish earthquakes dies out more rapidly than that of English earthquakes, implying that their foci are much less deeply seated. Now, in Scotland, it is an exception not to find a known fault in the position indicated by the seismic evidence. In England, comparatively few earthquakes can be associated with known faults. As exceptions may be mentioned the Exmoor earthquake of January 23, 1894, and the Malvern earthquake of September 27, 1907; and in both, the foci were obviously situated at a slight depth.¹⁸

A more significant test of the accuracy of these methods is the power of predicting the course of a fault. I have referred to the Ex-

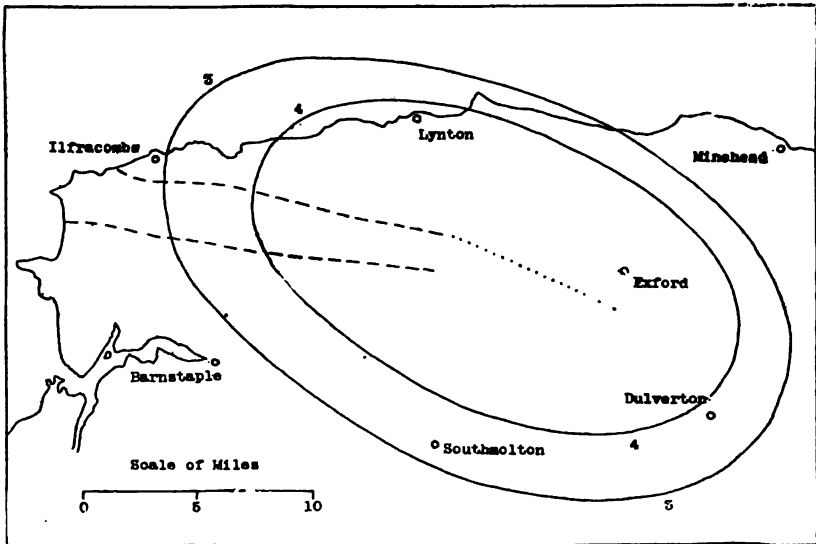


Fig. 3

moor earthquake of 1894, and in the accompanying map (Fig. 3) are given the isoseismal lines of this earthquake.¹⁹ They correspond to intensities 4 and 3. From the seismic evidence, we should conclude that the direction of the originating fault is E. 22° S., that the fault fades toward the south, and that the fault-line passes a short distance to the

¹⁸ The areas included within the isoseismal 4 of these earthquakes were respectively 228 and less than 200 square miles.

¹⁹ *Geological Magazine*, 8, 553-556. 1896.

north of the center of the innermost isoseismal. The probable course of the fault is represented by the dotted line on the map. A few months after this map was drawn, the late Dr. Henry Hicks published his first paper "On the Morte Slates and Associated Beds in North Devon and West Somerest."²⁰ "A great fault," he says, "extends continuously along the northern boundary of the Morte Slates from the coast near Ilfracombe to the Exe valley. On the south side there is evidence generally also of a well-marked fault." These faults hade to the south. In the map (Fig. 3), they are represented by broken lines as far as they are given in Dr. Hicks' map. Now, if the northern fault were to be deflected into the course indicated by the dotted line, it would satisfy all the seismic conditions. Without knowing if it were really so deflected, I sent a copy of the map to Dr. Hicks. He returned it with the course as mapped by him, and this coincides almost exactly with that suggested by the seismic evidence.

After an experience of thirty years in constructing isoseismal lines, I venture therefore to suggest that an arbitrary scale of seismic intensity may be of very considerable service in the study of earthquakes, provided that each degree of the scale is restricted to one test only, and that personal impressions, such as those depending on the degree of alarm excited, are excluded. I feel doubtful, however, whether it would be wise to attempt agreement in the adoption of one uniform scale in all civilized countries. Conditions vary from one country to another, and, so long as those conditions are known and so long as the scale is expressed in definite terms, it seems to me probable that the gain will be greater if each seismologist is left free to adopt that scale which is best adapted to the conditions under which he happens to work.

²⁰ *Quarterly Journal Geological Society*, 52, 254-273. 1896.



LOCATIONS BY KLOTZ STEREOGRAPHIC METHOD
Nos. 858, 865, and 946
1918

THREE REMARKABLE EARTHQUAKES IN 1918

By ERNEST A. HODGSON

From 1911 to 1915, inclusive, Dr. Klotz published yearly a list of the epicenters determined by the stereographic projection method from the data received at the Dominion Observatory from the various seismological stations. This series was continued by the present writer for 1916. All these issues have been published in *The Journal of the Royal Astronomical Society of Canada*.

The "Location of Epicenters for 1917-18," appearing shortly as a publication of the Dominion Observatory, has been delayed by various causes, not the least of which has been the delay in receiving the data from European stations during the years of the war. Many of the good stations of former years are missing in this work, Petrograd and Tiflis being perhaps the most vitally lacking ones.

One of the most interesting facts disclosed by the 1917-18 series has to do with the locations given by the data for Nos. 858, 865, and 946, dated respectively May 20, 1918, June 3, 1918, and December 2, 1918. The data from which these locations were made are given in full in the tabular matter below.

The stations are arranged in order of the magnitude of the difference between their O and the adopted O . This difference is given in column 7, headed D . The d and r are the values of the magnitudes given in the "Klotz Tables" for the stereographic projection of their Δ circles upon the plane of the equator. The other columns are self-explanatory.

No. 858. MAY 20, 1918

No.	Stations	<i>P</i>	<i>S</i>	Δ	<i>O</i>	<i>D</i>	<i>d</i>	<i>r</i>
		h. m. s.	h. m. s.	km.	h. m. s.	s.		
1	Athens.....	14 46 17	14 54 37	6820	14 35 59	0	720	802
2	Naples.....	14 45 46	14 53 36	6260	14 36 00	+ 1	628	689
3	Georgetown.....	14 44 53	14 51 59	5440	14 35 57	- 2	606	587
4	Paris.....	14 45 13	14 52 36	5750	14 35 57	- 2	480	573
5	Uccle.....	14 45 29	14 53 06	6020	14 35 57	- 2	465	596
6	Washington.....	14 44 51	14 51 55	5400	14 35 57	- 2	603	582
7	Barcelona.....	14 44 37	14 51 30	5200	14 35 56	- 3	557	541
8	Marseille.....	14 45 05	14 52 17	5540	14 36 02	+ 3	547	574
9	Coimbra.....	14 43 43	14 49 47	4300	14 36 03	+ 4	536	439
10	Dyce.....	14 45 44	14 53 30	6180	14 36 03	+ 4	385	587
11	La Paz.....	14 43 48	14 49 56	4370	14 36 03	+ 4	1960	1296
12	Ottawa.....	14 45 10	14 52 32	5740	14 35 55	- 4	528	589
13	Algiers.....	14 44 21	14 51 02	5000	14 35 54	- 5	613	541
14	Besancon.....	14 45 21	14 52 54	5940	14 35 54	- 5	510	604
15	Cheltenham.....	14 44 54	14 51 55	5340	14 36 04	+ 5	603	575
16	Berkeley.....	14 48 31	14 58 55	9280	14 36 05	+ 6	1086	1368
17	Budapest.....	14 46 15	14 54 27	6680	14 36 05	+ 6	547	702
18	Harvard.....	14 44 19	14 51 08	5130	14 35 43	- 6	541	528
19	Northfield.....	14 44 50	14 52 00	5520	14 35 49	-10	534	567
20	St. Louis.....	14 46 06	14 54 06	6440	14 36 10	+11	676	734
21	Vieques.....	14 42 30	14 47 30	3240	14 36 11	+12	802	412
22	Ithaca.....	14 44 53	14 52 14	5720	14 35 39	-20	568	603

$\phi = 7^{\circ}45'N.$; $\lambda = 36^{\circ}W.$; $O = 14^h 35^m 59^s$. G. M. T.

No. 865. JUNE 3, 1918

No.	Stations	<i>P</i>	<i>S</i>	Δ	<i>O</i>	<i>D</i>	<i>d</i>	<i>r</i>
		h. m. s.	h. m. s.	km.	h. m. s.	s.		
1	Barcelona.....	0 11 47	0 18 34	5080	0 03 14	- 1	552	526
2	La Paz.....	0 12 20	0 19 33	5560	0 03 16	+ 1	2680	2144
3	Uccle.....	0 12 53	0 20 37	6150	0 03 14	- 1	471	613
4	Zürich.....	0 12 43	0 20 17	5960	0 03 14	- 1	510	607
5	Paris.....	0 12 38	0 20 04	5820	0 03 18	+ 3	483	582
6	Algiers.....	0 11 16	0 17 40	4660	0 03 11	- 4	597	498
7	Georgetown.....	0 14 05	0 22 51	7340	0 03 19	+ 4	753	885
8	Athens.....	0 13 01	0 20 47	6190	0 03 20	+ 5	669	701
9	Coimbra.....	0 11 12	0 17 33	4620	0 03 10	- 5	548	476
10	Washington.....	0 14 04	0 22 48	7300	0 03 20	+ 5	748	877
11	Naples.....	0 12 45	0 20 14	5870	0 03 22	+ 7	603	634
12	Harvard.....	0 13 41	0 22 16	7120	0 03 07	- 8	665	810
13	Dyce.....	0 13 30	0 21 38	6600	0 03 25	+10	401	637
14	Ithaca.....	0 14 02	0 23 00	7560	0 03 04	-11	702	885

$\phi = 1^{\circ}S.$, $\lambda = 19^{\circ}45'W.$, $O = 0^h 03^m 15^s$. G. M. T.

No. 946. DECEMBER 2, 1918

No.	Stations	<i>P</i>	<i>S</i>	Δ	<i>O</i>	<i>D</i>	<i>d</i>	<i>r</i>
		h. m. s.	h. m. s.	km.	h. m. s.	s.		
1	Marseille.....	9 56 52	10 04 21	5870	9 47 29	0	564	618
2	Northfield.....	9 55 27	10 01 44	4540	9 47 30	+ 1	493	450
3	Ottawa.....	9 55 45	10 02 16	4800	9 47 30	+ 1	488	475
4	Washington.....	9 55 21	10 01 35	4480	9 47 28	- 1	559	466
5	La Paz.....	9 54 43	10 00 26	3930	9 47 31	+ 2	1805	1090
6	Coimbra.....	9 55 28	10 01 50	4630	9 47 25	- 4	549	478
7	Paris.....	9 56 52	10 04 25	5940	9 47 25	- 4	488	597
8	Vieques.....	9 52 44	9 56 52	2540	9 47 33	+ 4	771	315
9	Budapest.....	9 58 08	10 06 43	7120	9 47 34	+ 5	576	766
10	Georgetown.....	9 55 21	10 01 38	4540	9 47 24	- 5	562	473
11	Algiers.....	9 56 18	10 03 23	5450	9 47 23	- 6	638	602
12	Uccle.....	9 57 05	10 04 52	6200	9 47 23	- 6	473	619
13	Cheltenham.....	9 55 36	10 01 55	4580	9 47 36	+ 7	567	479
14	Barcelona.....	9 56 25	10 03 37	5540	9 47 22	- 7	574	585
15	Lemberg.....	9 58 30	10 07 24	7480	9 47 36	+ 7	561	803
16	Toronto.....	9 56 00	10 02 54	5220	9 47 18	-11	527	532
17	Agram.....	9 57 45	10 05 51	6560	9 47 42	+13	566	697
18	Zürich.....	9 57 10	10 05 08	6400	9 47 16	-13	533	664
19	Harvard.....	9 55 21	10 00 56	4220	9 47 48	+19	505	421

 $\varphi = 11^\circ \text{N.}, \quad \lambda = 44^\circ \text{W.}, \quad O = 9^{\text{h}} 47^{\text{m}} 29^{\text{s}}. \text{ G. M. T.}$

The map given shows the position of these locations with respect to the northeast coast of South America in a region which is generally supposed to be non-seismic. The data are given in detail in order to show that the epicenters deduced are correctly placed beyond any possibility of doubt within the limits of accuracy of the method employed and the data given.

None of these epicenters could have been known to those reading the records. Hence the readings are all entirely unbiased. That being the case the remarkable agreement of the *O*'s shows that, though refinements may later be applied to the tables at present in use, no considerable corrections are required, at least over the range tested by these epicenters.

It will be interesting to see whether the 1919-1920 series of "Locations of Epicenters" will disclose other earthquakes in this region.

DOMINION OBSERVATORY, OTTAWA
April 30, 1921.

TEMPERATURE CONTROL OF THE VERTICAL SEISMOGRAPH AT THE DOMINION OBSERVATORY, OTTAWA

By ERNEST A. HODGSON

The vertical seismograph at the Dominion Observatory is of the Wiechert type (80 kgm.) by Spindler and Höyer. It has given considerable trouble as regards temperature effects. These are now controlled and for six weeks past an unbroken series of records has been obtained without any tangling of the lines.

The arrangements for controlling the temperature are as follows: The wooden case, supplied by the makers to surround the spring and the grid, may be spoken of as Case 1. We have put about the whole instrument another case of wood, provided with the necessary openings with glazed doors, and with a flat roof, which we may speak of as Case 2. This case is four feet by six feet and stands six feet high. About it is another—Case 3. This last is large enough to give free air space 6 inches wide between the walls of Cases 2 and 3. It has a two-slope roof with peak eight feet high and eaves about six feet high. The gable ends are front and rear. Its doors, opposite those of Case 2, are of wood to exclude the light. An electric fan on the floor at the front between Cases 2 and 3 throws a continuous horizontal current of air upon a small electric heater (6A, 115V) beside it. The heater is controlled by a relay outside the cases. The heating current passes through the carbon points of the relay when these are closed by the thermostat. This latter is made of two strips eighteen inches long by two inches wide of brass and vulcanite, riveted rigidly together and hanging vertically with the contact points below. These points consist of a platinum plate on the double strip and a platinum pencil on an insulated post. The pencil is adjustable. The thermostat is mounted on the front face of Case 1 about half way up. It seems to be very important to place it at this point. Many other positions were tried and found to fail. The controlling current through the thermostat is small, hence the recovering spring on the relay is made weak. To insure that the points of the relay do not burn shut, an arrangement is provided, operated by the time signals, to tug open the points once each minute when there is no current flowing in the thermostat circuit.

A small door in Case 2, close to the floor and in the rear, admits air from the space between the cases, and the roof of the same case is

raised about two inches at its front edge, insuring a circuit of air about the instrument and preventing stratification. There is not enough movement to this to disturb the instrument.

The seismograph is now very sensitive. The period is 6 sec. and the magnification 160. A sensitizer to prevent friction at the writing point is provided. The sensitizer consists of a small electric buzzer, its interrupter shorted, its sound box removed, and running on the electric lighting circuit (60 cycle) with a lamp in series. This buzzer, attached rigidly to the small post supporting the stylus bearings, imparts a continuous small vibration without sound. This vibration does not register on the seismogram, as its direction is mostly vertical, very rapid and extremely small. In this adjustment the instrument records all the earthquakes recorded on the instruments with optical registration.

A thermograph record from a small Richard instrument inside Case 2 shows no variation for an entire week. It is not to be compared, however, to the testimony furnished by the untangled lines on the seismogram that the temperature is under complete control.

One point which for a long time caused failure must be mentioned. The instrument must be kept in darkness. An electric light inside Case 2 is turned on for just long enough to change the instrument—about a minute. The winding is arranged to be done outside. The thermostat is very sensitive. The light turns it off too soon, due to local heating, and the case cools. If left on for five minutes it upsets the control for at least an hour.

DOMINION OBSERVATORY, OTTAWA

May 3, 1921.

AERIAL OBSERVATION OF EARTHQUAKE RIFTS

By BAILEY WILLIS

The Seismological Society of America is interested in mapping the earthquake rifts of California, with a view to increasing our knowledge of the structures related to earthquakes and to promoting security in the engineering work of the State. Data of a general and comprehensive character already exist in published and unpublished maps, but additional surveys are desirable. Faults may be located in several ways, and it is possible that a method of tracing them may be developed with the airplane, as was first suggested to the writer by H. O. Wood. To test the idea, a flight was made by me from San Francisco to Los Angeles and return on June 9th and 11th, so far as practicable over the San Andreas Rift, to observe and photograph it.

The plane was furnished by the Air Service of the United States Army, by courtesy of Major H. H. Arnold, under authority of General Menoher, Chief. The aviator was Sergeant Fowler. The photographic equipment consisted of a mapping camera, K. 1 model, fixed in the bottom of the plane. This camera is designed to take successive pictures automatically and can be so adjusted for the altitude of the plane and the apparent air speed that the exposures take a small overlap. The views can therefore be combined in a continuous mosaic. Theoretically the action should be perfect and the continuity of pictures unbroken. In practice, the tilting of the plane is equivalent to turning a camera through a greater or less angle on a tripod, and successive views may jump interspaces of greater or less extent. The only apparent remedy, with this type of camera, would seem to be a repeat, a recourse which is practicable when flying over a restricted area, but impracticable in a flight between distant landing fields.

The flights here noted covered a course of approximately 400 miles each way and were made in 4 hours 40 minutes on the southward trip and 4 hours 13 minutes on the northward.

The San Andreas Rift, the object of observation, is that major continental structure which extends from Humboldt County in Northern California to the Mojave Desert in the southern part of the State, a distance of about 600 miles. It is an ancient fault, the locus of innumerable movements, which have given rise to pronounced topographic features. Displacements have been upward or downward or lateral

along different sections of the fault or during different movements along the same section. We have yet much to learn about the effects of faulting expressed in the details of geology along the rift.

The earthquake of April, 1906, produced marked surface features, which were carefully studied by Branner, Gilbert, Lawson, and other geologists and which have been fully described in the report of the California State Earthquake Commission, publication 87 of the Carnegie Institution of Washington. One is often asked to what extent those features are still visible, and the answer is that much depends upon the climatic conditions of any selected section. Where rainfall is abundant, vegetation vigorous, and erosion efficient, there is not much to be seen after fifteen years; but under arid conditions the marks of the disturbance of 1857 survive plainly.

The essential fact is that the rift is a line, and features peculiar to it must fall into line. The general position and course of this rift being known, the observer was constantly noting valleys, lakes and ponds, ravines, washes, or scars on the surface, which lined up with one another. From over Mussel Rock, where the rift cuts the shore, the range along the rift was plainly that of the axis of San Andreas and Crystal Springs Lakes, and was continued in the valley through Searles Lake and beyond to Black Mountain. Stevens Creek heads in that summit on the rift and flows for six miles along it. Thus for a distance of thirty-three miles the earthquake line is marked by major features of the topography, by valleys which are due to the coöperation of displacement and erosion. Similar valleys might be produced by erosion alone, and since the rocks are hidden by water, soil, and vegetation, the aerial observer could not see the displacement. In this section the observer could infer, but could not demonstrate, the existence of the rift.

Continuing southeastward beyond Wright's Station on the Santa Cruz branch of the Southern Pacific the rift traverses the western slope of the Santa Cruz Mountains, near the summit, and determines the course of numerous small valleys which are the head valleys of streams that flow south to Monterey Bay, but which, contrary to what would be expected, range themselves into line parallel with the crest of the mountains. Along this same line there are numerous landslide scars and small ponds. No one or small group of these features would necessarily indicate the existence of the rift, but their alignment over a distance of twenty-five miles would be strong presumptive evidence of it, and that alignment can be seen from the airplane. The only other way in which it can be demonstrated is by a study of an accurate topographic

map, which is in itself, as it were, an airplane view. Thus, for any section of an earthquake track which might be indicated by features similar to those occurring on the western slopes of the Santa Cruz Mountains, observation by airplane would constitute a valuable method of investigation.

Passing to the middle section of the earthquake rift, where the aridity of the climate prevents the growth of vegetation and limits the destructive work of erosion, the marks of the earthquake became more distinct and more continuous. Thus my notes read: "Mustang Ridge and Peach Tree Valley, rift shows in serpentine slides in the ridge. Temblor Range, the line of the rift shows like a light soil streak for miles ahead. Over Carrizo Plains at Wolforts, rift shows up in a line of white washes easily lined up," and a little farther along: "Rift shows plainly like a canal ditch."

The ditch-like character of the rift along the northeast slope of Carrizo Plains has been noted by Fairbanks and others. It is remarkable, plainly visible from an altitude of 12,000 feet, like a large empty irrigation canal. I could see it perhaps ten miles ahead till it was lost in the rosy dust haze.

At this point the aviator passed me a note: "Forty minutes more gas." I scaled off the distance to Bakersfield, the only landing place. It was thirty-five minutes away, and we turned from the rift.

Returning from Los Angeles on the 11th we flew along the southeastern section of the rift from Tejon Pass up Cuddy Valley to San Emigdio Peak. In this stretch it is marked by springs which give rise to alkali patches or to green mallins, the marshes peculiar to seepages in arid valleys. Its features are easily traceable because of their linear continuity.

Photographing from an airplane is less satisfactory than observing. When the camera is fixed on the plane, as it must be to secure continuity of views, it swerves with every swing of the ship, and at a distance of one or two miles from the landscape a slight swing makes a big miss. I myself lost the sense of horizontal or vertical and was quite unconscious of the fact that the camera was winking at the mountain slope when I thought it was photographing the lake. A clinometer would enable the observer to steer a better course to get what he wanted.

In the vertical view features are flattened. This is true for vision and is even more pronouncedly true in photographs. It would be desirable therefore to observe during the earlier and later hours of the

day when shadows are strong. The swiftness of flight makes this practicable, since miles become short when expressed in minutes, and a distant field of study can be reached quickly. Photography, however, requires the strongest light possible because the exposure must be very brief when the camera is making a hundred miles an hour, and this requirement limits the available hours to those when shadows are weak or lacking. The effect of this limitation is yet to be worked out, but since rift features are to a great extent relief features, it is of consequence.

So far as the trial flights of June 9th and 11th go they seem to demonstrate that aerial observation of a linear structural feature such as an earthquake rift, is practicable. If one end of a rift be known, it can be followed by a man skilled in the interpretation of topographic forms. Or if a line of features be detected, it may be so traced as to demonstrate their continuity and to facilitate the closer examination which may be necessary to prove the existence of a fault. I conclude that the airplane can be used to advantage as a means of rapid geologic reconnaissance to map large structural features.

SEISMOLOGICAL NOTES

Lompoc, California, December 5, 1920.—Mr. Edward J. Porteous reports having felt an earthquake at White Hills, 4.6 miles south of Lompoc, on December 5, 1920, at 3:59 a. m. There was general awakening of those asleep at Lompoc and White Hills, but no damage was reported. There were three shocks of four, six, and three seconds duration. The time given for this shock is eleven minutes later than one reported by Mr. Fletcher as having been felt in Los Angeles.¹

Los Angeles, California, March 5, 1921.—A shock of intensity II, Rossi-Forel scale, duration two seconds, was reported by Dr. Titian Coffey of Los Angeles as having occurred between 12 and 1 o'clock a. m. on March 5th.

Holbrook, Arizona, April 6, 1921.—Two earthquake shocks of about thirty seconds duration are reported to have been felt at Holbrook, Arizona, on April 6th. The time of day is not given. Desks and chairs were moved, windows and dishes rattled, and one large plate-glass window was broken. The same shock is reported to have been felt as far west as Winslow and as far east as Gallup, N. M.

Los Angeles, California, April 21, 1921.—An earthquake of intensity III, Rossi-Forel scale, was reported from Los Angeles by nine different observers at 7:38 a. m. One observer located at Hollywood reports an intensity of V.

Riverside, California, April 27, 1921.—The United Press reports that two slight earthquake shocks were felt in Riverside at about 7 a. m. on April 27th. There was no damage, but windows and dishes were rattled.

Los Angeles, California, May 2, 1921.—Professor C. W. Cook, of the University of Southern California, reports having felt an earthquake on May 2nd, at 5:43 a. m., of intensity III, Rossi-Forel scale. The duration was from seven to ten seconds.

¹ See *Bulletin of the Seismological Society of America*, 10, 317.

Los Angeles, California, May 4, 1921.—Mr. David C. Thompson, of the United States Geological Survey, reports having felt an earthquake in Los Angeles of intensity II, Rossi-Forel scale, at 8:42 a. m., on May 4th.

Imperial, California, June 17, 1921.—Mr. J. M. Bartley reports having felt a light shock at Imperial on June 17th at 2 a. m.

SEISMOLOGICAL REPORTS RECEIVED

AMERICA

Cambridge, Mass.—Seismographic Station, Harvard University. Reports from January 1, 1921, to February 11; February 19 to April 7, 1921.

Denver, Colo.—Jesuit Seismological Service, Sacred Heart College. Report No. 5, May 1 to May 31, 1921; Seismic Record No. 4, April 30, and No. 6, June, 1921.

Ithaca, N. Y.—Seismograph Station, Cornell University. Reports Nos. 113 and 114, March 1 to April 30, 1921.

Ottawa, Canada.—Earthquake Station, Dominion Observatory. Reports Nos. 10 to 18, April 1 to June 30, 1921.

Washington, D. C.—Seismological Bulletin of the Georgetown University, Nos. 61 and 63, February 1 to 28, April 1 to 31, 1921; compiled press dispatches from February 3 to May 15, 1921.

ASIA

Zi-Ka-Wei, China.—Bulletin Sismique de l'Observatoire de Zi-Ka-Wei, Nos. 1 and 2, January 2 to March 4, 1921.

AUSTRALIA

Sydney, N. S. W.—Seismological Bulletin, Riverview College Observatory, Nos. 10 to 12, October 1 to December 31, 1920.

EUROPE

Barcelona, Spain.—Estacion sismica del Observatorio Fabra, Nos. 73 to 75, September 11 to December 31, 1920.

Blackburn, England.—Earthquake Records, Stonyhurst College Observatory, January 2 to April 25, 1921.

Coimbra, Portugal.—Boletim Sismico do Observatorio Meteorologico da Universidade, Nos. 1 to 5, January 1 to May 23, 1921.

Jena, Germany.—Mitteilungen der Deutschen Erdbebenwarten, Nos. 1, 5, and 9, September 6, 7, and 20, October 18, and December 16, 1920; Mitteilungen über die beiden Erdbeben in der Argentinischen Provinz Mendoza am 17. Dezember 1920; Mitteilungen über Erdbeben im Jahre 1912; Tektonische Übersicht von Japan.

Hamburg, Germany.—Monatliche Mitteilungen der Hauptstation für Erdbebenforschung am Physikalischen Staatsinstitut, Nos. 1 to 5, January 2 to May 28, 1921.

Netherlands.—Seismological Bulletin, Royal Netherlands Meteorological Institute, Nos. 1 to 8, January 1 to February 27, 1921.

NEW ZEALAND

Wellington, New Zealand.—Earthquake Reports, Hector Observatory, January and February, 1921.

PHILIPPINE ISLANDS

Manila, P. I.—Seismological Bulletin of the Observatory, Nos. 1 to 5, January 1 to March 31, 1921.

PUBLICATIONS RECEIVED

"Über die Fortpflanzungsgeschwindigkeit der seismischen Oberflächenwellen Längs kontinentaler und ozeanischer Wege," von E. Tams. Separat-
abdruck aus dem *Centralblatt für Mineralogie, Geologie und Paläontologie*,
Jahrg. 1921, No. 2 u 3.

"Bibliografia Generale dei Terremoti," by G. Agamennone. Estratto dal
Bollettino della Società Sismologica Italiana, 22, fasc. 5-6, Anno 1919.

"Macrosismi Avvertiti in Italia nell' anno 1918," by G. Martinelli, Estratto
dal *R. Ufficio Centrale di Meteorologia e Geodinamica*.

"Breves Apuntes sobre los Fenomenos Volcanicos," por Manuel Muñoz
Lumbier, Edición del *Boletín Minero*, Mexico.

Boletín Mensual del Observatorio del Ebro, 11, Núms. 1 to 9 Tortosa, Spain.

Boletín Mensual, Oficina Meteorologica Nacional, Año III, Número 7,
Buenos Aires, Argentina.

"Analysis of Earthquake Waves" by Otto Klotz, from the *Transactions*
of the *Royal Society of Canada*, 14, Third Series, 1920. Ottawa, 1921.

"Die seismischen Verhältnisse des Europäischen Nordmeeres und seiner
Umrandung" von Dr. Ernst Tams.

Bollettino della Società Sismologica Italiana, 22, No. 5-6. Modena, 1919.

"Macrosismi avvertiti in Italia nell' anno 1919" by G. Martinelli. Estratto
dal *Bollettino della Società Sismologica Italiana*, 22, fasc. 5-6, Anno 1919.

Bulletin of the Imperial Earthquake Investigation Committee, 9, No. 3,
Tokyo, March, 1921.

University of California Publications. Bulletin of the Seismographic
Stations, No. 20, pp. 405-422, "The Registration of Earthquakes at the Berkeley
Station and at the Lick Observatory Station from April 1, 1920, to September
30, 1920," by Lewis A. Bond.

Georgetown University Publication. Bulletin of the Seismographic Station,
No. 5, pp. 1-25, April 1, 1921, "The Registration of Earthquakes at the George-
town Station from January 1, 1920, to January 1, 1921," by F. A. Tondorf, S. J.

Boletín Mensual, Oficina Meteorologica Nacional, Año III, Número 8,
9, and 10, Buenos Aires, 1921.

Boletín Mensual del Observatorio del Ebro, 11, Nums 10-11-12, Tortosa.

"Resumen de las Observaciones solares, electro-meteorológicas y geofísicas
efectuadas durante 1920," *Boletín del Observatorio del Ebro*, 11, Tortosa, 1921.

"Zur Entstehung der Vulkangruppe Raudholar in Island" von A. Sieberg.
Sonderabdruck aus der *Zeitschrift für Vulkanologie*, Band 6. Berlin.

Catalogue of Philippine Earthquakes, 1919. Reprint from the *Weather*
Bulletin for December, 1919.

Annuaire de l'Institut de Physique du Globe 1919 Universite de Strasbourg, Premiere partie; Meteorologie, et deuxime partis: Sismologie, Strasbourg, 1920.

Seismische Registrierungen in de Bilt, Koninklujk Nederlandsch Meteorologisch Instituut, No. 108, 1917, Utrecht, 1920.

"Studi Vulcano-Gravimetrici in Memoria del barone Orlando Eötvös" by Rado de Kövesligethy. Estratto dal *Bollettino della Societa Sismologica Italiana*, 22, fasc. 5-6, anno 1919, Modena, 1920.

"Geoide e Bilancia di Torsione" by Rado de Kövesligethy. Estratto dal *Bollettino della Societa Sismologica Italiana*, 22, fasc. 5-6, anno 1919, Modena, 1920.

"Sulla Previsione Scientifica dei Terremoti" by R. de Kövesligethy. X Congresso Internazionale de Geografia, Roma, 27 Marzo—Aprile, 1913, Roma, 1915.

Bulletin Annuel de l'Observatoire Meteorologique du Seminarie—College St. Martial, Annee 1919, Port-au-Prince, Haiti.

"Le Tremblement de Terre du Kan-Sou (Chine)" par le R. P. E. Gherzi, S. J., *Note de Sismologie*, Observatoire de Zi-Ka-Wei, 16 Decembre, 1920.

"Memorias y Trabajos de Vulgarizacion Cientifica," *La Estacion Sismologica y el Observatorio Astronomico y Meteorologico de Cartuja, (Granada)*.

MINUTES OF THE MEETING OF THE BOARD OF DIRECTORS OF THE SEISMOLOGICAL SOCIETY OF AMERICA

May 25, 1921.

In the absence of the President, the meeting was called to order by Vice-President Wood at 3 p. m., in the rooms of the Engineers' Club, 57 Post Street, San Francisco, California. Directors Lawson, Townley, and Wood were present. Mr. Willis came in later.

Various matters were considered by the Board and disposed of as indicated under the following heads:

(a) The minutes of the meeting of the Board of Directors of February 7, 1921, were read and approved.

(b) The report of the Nominating Committee was read by the Secretary and ordered filed and printed as a part of these minutes.

(c) The report of the Board of Election was also read and ordered filed and printed.

(d) After being duly nominated, the following officers were elected for the year:

President	- - - - -	BAILEY WILLIS
First Vice-President	- - - - -	R. W. SAYLES
Second Vice-President	- - - - -	H. O. WOOD
Third Vice-President	- - - - -	C. F. TOLMAN, JR.
Secretary-Treasurer	- - - - -	S. D. TOWNLEY

(e) The report of the Secretary-Treasurer for the year ending April 2, 1921, was read and accepted and ordered printed as a part of these minutes.

(f) The report of the Auditing Committee was also read and ordered filed and printed.

(g) The following named persons were elected to membership in the Society:

Dr. William Bowie, Washington, D. C.	A. M. McDearmott, Pasadena, Cal.
H. T. Clifton, Pasadena, Cal.	K. P. McDearmott, Pasadena, Cal.
Robert L. Faris, Washington, D. C.	F. O. Martin, Bogotá, Colombia, S. A.
Dr. P. Maxwell Foshay, Montclair, N. J.	Stephen Mather, Washington, D. C.
Col. E. Lester Jones, Washington, D. C.	Richard L. Russell, Los Angeles, Cal.
Theodore C. Kistner, San Diego, Cal.	Muriel W. Sweet, Pasadena, Cal.
	Edgar W. Woolard, Washington, D. C.
	Miss Lucy Youse, Los Angeles, Cal.

(h) The following named institutions were placed on the list of subscribers to the BULLETIN:

Chuo-Kishodai, Tokyo, Japan.
Messrs. Kemink and Son, Utrecht, Netherlands.
Pomona College Library, Claremont, Cal.
Seismological Institute, Tokyo, Japan.

(i) The Secretary reported the death of three members of the Society:

Mr. Charles Page, San Francisco, Cal.

Mr. E. E. Prowell, Phoenix, Ariz.

Mr. Sam B. Stoy, San Francisco, Cal.

The Secretary also reported the resignation of two members:

Frederick J. Koster, San Francisco, Cal.

J. Leroy Nickel, Menlo Park, Cal.

(j) The salary of the Secretary-Treasurer was fixed at \$20.00 per month for the fiscal year 1921-1922.

(k) A letter from Dr. T. A. Jaggar, Jr., urging the establishment of a Volcano Research Observatory on Lassen Peak, was presented to the Board and after discussion, was order referred to the Scientific Committee for consideration and report.

(l) Several requests for the exchange of publications were presented by the Secretary. After considerable discussion the Board reaffirmed its former position of not establishing a list of exchanges.

(m) The Secretary referred to the condition of the finances of the Society and stated that the cost of printing would be higher this year than ever before. It was shown that it would be impossible to continue issuing the BULLETIN of the Society unless some additional funds could be obtained. The President was instructed to appoint a committee of three, with power to add to its number if thought best, to investigate the question of finances and to report ways and means of increasing the income of the Society.

(n) At the suggestion of Director Lawson, the following resolution was adopted:

WHEREAS, It has been found that the region about the Bay of San Francisco is in a condition of slow motion due to strain in the earth's crust, which is relieved from time to time by sudden fault-slips thus causing earthquakes;

AND WHEREAS, Both the strain creep and its sudden relief cause changes in the geographical positions of the region so that the latitude and longitude vary in comparatively short periods of time;

AND WHEREAS, There is an active fault, known as the San Andreas fault, spanning the entrance to the harbor of San Francisco, which is a possible menace to the safety and availability of the entrance to the port;

AND WHEREAS, It is most desirable to obtain all possible scientific information regarding the movements of the earth's crust, and in particular the movements related to the San Andreas fault;

AND WHEREAS, The United States Coast and Geodetic Survey is the most efficient agency for obtaining this information;

THEREFORE BE IT RESOLVED, That it is the sense of the Board of Directors of the Seismological Society of America that the United States Coast and Geodetic Survey should be charged with the duty of determining the amount of change in the geographical positions in regions of seismic activity and that the necessary appropriation for carrying on this work, in addition to the regular work of the Survey, be made in the annual budgets.

BE IT FURTHER RESOLVED, That a copy of this resolution be transmitted to the Honorable the Secretary of Commerce and to the Senators and Representatives from California in the Congress.

Adjourned at 5:00 p.m.

S. D. TOWNLEY,
Secretary.

REPORT OF THE NOMINATING COMMITTEE OF THE SEISMOLOGICAL SOCIETY OF AMERICA

Nominations for members of the Board of Directors, made at the meeting of the Nominating Committee, held on February 18, 1921, follow:

J. C. BRANNER, Geologist, Stanford University, Cal.
W. W. CAMPBELL, Astronomer, Lick Observatory, Mt. Hamilton, Cal.
E. F. DAVIS, Geologist, Berkeley, Cal.
H. C. HOOVER, Mining Engineer, Stanford University, Cal.
OTTO KLOTZ, Astronomer and Seismologist, Ottawa, Canada.
A. C. LAWSON, Geologist, University of California, Berkeley, Cal.
G. D. LOUDERBACK, Geologist, University of California, Berkeley, Cal.
C. F. MARVIN, Meteorologist, U. S. Weather Bureau, Washington, D. C.
A. G. MCADIE, Meteorologist, Blue Hill Observatory, Readville, Mass.
WILLIAM MULHOLLAND, City Engineer, Los Angeles, Cal.
M. M. O'SHAUGHNESSY, City Engineer, San Francisco, Cal.
R. W. SAYLES, Geologist, Harvard University, Cambridge, Mass.
STEPHEN TABER, Geologist, University of South Carolina, Columbia, S. C.
C. F. TOLMAN, JR., Geologist, Stanford University, Cal.
S. D. TOWNLEY, Astronomer, Stanford University, Cal.
H. W. TURNER, Mining Geologist, San Francisco, Cal.
BAILEY WILLIS, Geologist, Stanford University, Cal.
H. O. WOOD, Seismologist, National Research Council, Washington, D. C.

R. S. HOLWAY, *Chairman.*

REPORT OF THE BOARD OF ELECTION OF THE SEISMOLOGICAL SOCIETY OF AMERICA.

San Francisco, Cal., April 2, 1921.

TO THE BOARD OF DIRECTORS OF THE SEISMOLOGICAL SOCIETY:

We, the undersigned judges of election, certify that 149 ballots for directors were cast at the annual election, held in San Francisco on this date, with the following result:

J. C. Branner	- - - - -	139	A. C. Lawson	- - - - -	124
W. W. Campbell	- - - - -	131	G. D. Louderback	- - - - -	87
E. F. Davis	- - - - -	50	C. F. Marvin	- - - - -	101
H. C. Hoover	- - - - -	100	A. G. McAdie	- - - - -	103
Otto Klotz	- - - - -	111	Ralph Arnold	- - - - -	1

Wm. Mulholland - - - - -	86	S. D. Townley - - - - -	128
M. M. O'Shaughnessy - - - -	63	H. W. Turner - - - - -	48
R. W. Sayles - - - - -	94	Bailey Willis - - - - -	99
Stephen Taber - - - - -	79	H. O. Wood - - - - -	129
C. F. Tolman, Jr. - - - - -	91		

The following named, being the twelve receiving the highest number of votes, are declared elected Directors of the Society for the year 1921-1922:

1. J. C. Branner	5. A. C. Lawson	9. H. C. Hoover
2. W. W. Campbell	6. Otto Klotz	10. Bailey Willis
3. H. O. Wood	7. A. G. McAdie	11. R. W. Sayles
4. S. D. Townley	8. C. F. Marvin	12. C. F. Tolman, Jr.

The amendments to the By-Laws of the Society increasing the dues and the price of subscription to the BULLETIN from two to three dollars per year were both carried. The vote on the amendment concerning dues was 124 yes, and 11 no. The vote on the amendment increasing the subscription price was 129 yes, and 6 no.

D. S. RICHARDSON
S. EINARSSON.

Board of Election.

REPORT OF SECRETARY-TREASURER OF THE SEISMOLOGICAL SOCIETY OF AMERICA

From April 3, 1920, to April 2, 1921.

The activities of the Seismological Society of America were confined, during the year 1920-21 to the investigation of three earthquakes occurring in California, and to the publication of the BULLETIN.

The earthquakes referred to are those which occurred at Inglewood on June 21st, at Los Angeles on July 16th, and near San Jose on September 9th. The first two of these were investigated by Dr. Stephen Taber, aided by several members of the Society living in Southern California. The third was investigated by Mr. Frederick P. Vickery. The expenses of these investigations were defrayed from the funds provided for this purpose by the American Association for the Advancement of Science, and the results of the investigations have been published in the various numbers of the BULLETIN.

During the summer and autumn months of 1920, a Southwest Section of the Society was formed. The headquarters of this section are in Los Angeles. A short account of its activities was printed in the March, 1921, number of the BULLETIN.

Volume 10 of the BULLETIN, containing 348 pages and twenty-seven plates, was issued during the calendar year 1920. This is the largest volume thus far issued and its publication was made possible by generous gifts from three sources. Dr. J. C. Branner gave \$451.79 toward the expense of publishing the June and September numbers of the BULLETIN; the National Research

Council of Washington, D. C., gave \$300.00 toward the expense of publishing the December number; and the Hawaiian Volcano Research Society gave \$688.56 to pay for printing Dr. Jaggar's article in the December number.

The total number of members of the Society and subscribers to the BULLETIN is now 447, an increase of 61 during the year. The increase is due largely to the efforts of several members living in or near Los Angeles.

Six members were lost through death: Mr. Maxwell Hall, Jamaica, W. I.; Mr. Homer Hamlin, Los Angeles, California; Mr. Orlis I. Kennedy, San Bernardino, California; Judge Curtis H. Lindley, San Francisco, California; Major H. F. Perry, Palo Alto, California; and Professor L. V. Pirsson, New Haven, Connecticut.

The financial report is as follows:

<i>Dr.</i>		GENERAL FUND	
To balance, April 3, 1920.....	\$	0.00	
Dues and subscriptions		881.18	
Reprints		184.55	
Sale of publications		28.67	
Transfer from Sayles Fund, interest.....		227.50	
Transfer from Life Membership Fund, interest.....		24.20	
Gift from J. C. Branner		451.79	
Gift from National Research Council		300.00	
Transfer from American Association fund		8.00	
Total		\$2105.89	
<i>Cr.</i>			
By Stanford University Press, printing BULLETIN, balance on			
Volume 9	\$	122.85	
Stanford University Press, printing BULLETIN, Volume 10			
(see note)		1143.15	
Stanford University Press, reprints.....		307.60	
Stanford University Press, miscellaneous printing.....		20.00	
Stanford University Press, envelopes.....		27.25	
Commercial Art Co., illustrations.....		156.14	
Stanford University Post Office, second class postage.....		8.73	
Stanford University Post Office, foreign postage.....		10.17	
Stanford University Post Office, miscellaneous postage.....		11.11	
Stanford University Post Office, stamped envelopes.....		22.46	
Bank of Palo Alto, rent safety deposit box.....		3.00	
Bank of Palo Alto, exchange.....		.72	
Pacific Division, A. A. A. S., dues 1921.....		5.00	
L. E. Porter, drawing map.....		8.00	
Stanford Bookstore, letter file.....		1.00	
S. D. Townley, salary of secretary-treasurer.....		240.00	
Balance, April 2, 1921.....		18.71	
Total		\$2105.89	

(NOTE: There is an unpaid balance of \$538.90 for printing the December number of the BULLETIN. We expect a grant from the Volcano Research Association of Hawaii to cover this.)

<i>Dr.</i>		LIFE MEMBERSHIP FUND
To balance, April 3, 1920.....	\$	600.00
Interest from Berkeley Bank of Savings and Trust Company.....		24.20
Total	\$	624.20
<i>Cr.</i>		
By interest, transferred to General Fund.....	\$	24.20
Balance, April 2, 1921		600.00
Total	\$	624.20
<i>Dr.</i>		SAYLES FUND
To balance, April 3, 1920.....	\$	4000.00
Interest from Mutual Building and Loan Association of San Jose and College Park.....		60.00
Interest from Palo Alto Mutual Building and Loan Association....		120.00
Interest from Fifth U. S. Liberty Loan Certificates.....		47.50
Total	\$	4227.50
<i>Cr.</i>		
By transfer to General Fund, interest	\$	227.50
Balance, April 2, 1921.....		4000.00
Total	\$	4227.50
<i>Dr.</i>		AMERICAN ASSOCIATION FUND
To balance, April 3, 1920.....	\$	417.91
Grant from A. A. A. S., March 18, 1921.....		200.00
Interest, Bank of Palo Alto.....		16.05
Total	\$	633.96
<i>Cr.</i>		
By Stephen Taber, investigation of Inglewood and Los Angeles earthquakes	\$	156.33
J. C. Branner, tracing cloth.....		1.20
C. H. Dobbel, drawing map, Inglewood.....		12.25
W. Kemnitzer, drawing map, Inglewood.....		34.65
F. P. Vickery, investigation of San Jose earthquake.....		32.50
L. E. Porter, drawing map of San Jose earthquake.....		8.00
Balance, April 2, 1921.....		389.03
Total	\$	633.96

S. D. TOWNLEY, *Secretary-Treasurer.*

REPORT OF THE AUDITING COMMITTEE OF THE SEISMOLOGICAL
SOCIETY OF AMERICA

San Francisco, April 28, 1921.

To the Seismological Society of America:

Your Auditing Committee submits the enclosed report of the accounts of the society, which has been prepared under its supervision, by Mr. L. E. Townsend. It shows disbursements have all been properly accounted for, and that the income receipts from dues, subscriptions, etc. have, from all evidence, been properly accounted for.

Yours faithfully,

J. K. MOFFITT
J. A. TAFF
BERNARD BENFIELD

Stanford University, Cal., April 5, 1921.

TO THE AUDITING COMMITTEE OF THE
SEISMOLOGICAL SOCIETY OF AMERICA.

DEAR SIRs:

At the request of Dr. S. D. Townley, Secretary-Treasurer of the Seismological Society of America, I have this day examined the contents of Safety Deposit Box No. 8, at the Bank of Palo Alto, and have found therein the following named securities, the first three made out in the name of the Seismological Society of America:

Palo Alto Mutual Building and Loan Association,	
Certificate of Deposit No. 351.....	\$ 1000.00
Certificate of Deposit No. 352.....	1000.00
Mutual Building and Loan Association of San Jose and College Park,	
Certificate of stock, No. 621.....	1000.00
Fifth U. S. Liberty Loan Certificate, No. E 1019470.....	1000.00
Total	\$ 4000.00

Very truly yours,

J. A. TAFF.

April 27, 1921.

TO THE AUDITING COMMITTEE OF THE
SEISMOLOGICAL SOCIETY OF AMERICA:

The undersigned has examined the financial statement embodied in the report of the Secretary-Treasurer of the Society, which represents the receipts and disbursements of the Society for the fiscal year, beginning April 3, 1920, and closing April 2, 1921.

The membership and subscription records appear to be in order.

The statement of the commercial account submitted by the Bank of Palo Alto, showing a balance of \$18.71, is correct. The General Fund Account checks correctly. The amount shown in the Secretary-Treasurer's report as to the funds held for the Life Membership Fund, Sayles Fund and American Association Fund are deposited as follows:

AMERICAN ASSOCIATION FUND

Account No. 2797—Funds deposited with the Bank of Palo Alto in the name of the Seismological Society of America; balance.....\$389.03

LIFE MEMBERSHIP FUND

Account No. 8521—Deposited with the Berkeley Bank of Savings in the Name of the Seismological Society of America; balance.....\$600.00
Savings pass books were submitted by the Secretary-Treasurer showing that the above balances are on deposit in the banks above stated.

SAYLES FUND

This account, showing a balance of \$4000.00, is certified to as being correct by the statement appended hereto and signed by Mr. J. A. Taff, a member of the Auditing Committee.

Respectfully submitted,

L. E. TOWNSEND.

ROSSI-FOREL SCALE OF EARTHQUAKE INTENSITIES

- I. **Microseismic shock:** recorded by a single seismograph or by seismographs of the same model, but not by several seismographs of different kinds; the shock felt by an experienced observer.
- II. **Extremely feeble shock:** recorded by several seismographs of different kinds; felt by a small number of persons at rest.
- III. **Very feeble shock:** felt by several persons at rest; strong enough for the direction or duration to be appreciable.
- IV. **Feeble shock:** felt by persons in motion; disturbances of movable objects, doors, windows; creaking of ceilings.
- V. **Shock of moderate intensity:** felt generally by everyone; disturbance of furniture, beds, etc., ringing of swinging bells.
- VI. **Fairly strong shock:** general awakening of those asleep; general ringing of house bells; oscillation of chandeliers; stopping of pendulum clocks; visible agitation of trees and shrubs: some startled persons leave their dwellings.
- VII. **Strong shock:** overthrow of movable objects; fall of plaster; ringing of church bells; general panic, without damage to buildings.
- VIII. **Very strong shock:** fall of chimneys, cracks in walls of buildings.
- IX. **Extremely strong shock:** partial or total destruction of some buildings.
- X. **Shock of extreme intensity:** great disaster, buildings ruined, disturbance of the strata, fissures in the ground, rock-falls from mountains.

Bulletin of the Seismological Society of America

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SEPTEMBER-DECEMBER, 1921

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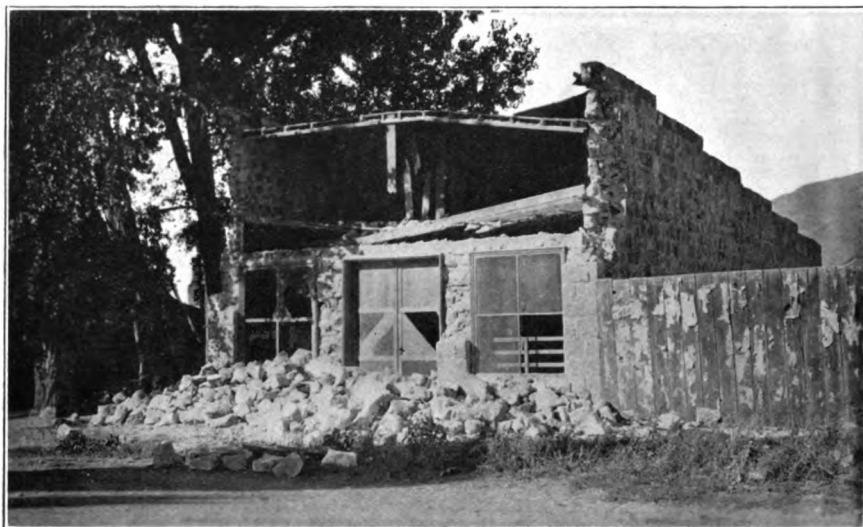


Fig. 1. One of the oldest buildings in Elsinore, built of angular fragments of lava. This illustrates a poor type of construction. The mortar was evidently weak and the front of the building was not tied in.



Fig. 2. The Mormon Church house at Elsinore. This building was practically undamaged, which illustrates the fact that it is possible to construct earthquake-proof buildings of brick.

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Nos. 3 and 4

THE ELSINORE EARTHQUAKES IN CENTRAL UTAH, SEPTEMBER 29 AND OCTOBER 1, 1921

By FREDERICK J. PACK

Three distinct earthquakes of considerable intensity were experienced at Elsinore, Sevier County, Utah, on September 29 and October 1, 1921. The writer left for the field immediately on receipt of information of the disaster and had the unusual good fortune to be on the ground when the last of the three disturbances arrived. Professor Bailey Willis was kind enough to invite the writer to make an investigation at the expense of the Seismological Society of America, but before his communication was received practically all of the data contained in this article had been gathered. Through his invitation they have been prepared for publication in the present form.

GEOGRAPHY AND TOPOGRAPHY

Elsinore is a small town of less than one thousand inhabitants and is situated in a long north-south valley of the High Plateau province of south-central Utah. It was founded by the Mormon pioneers, and in many ways is characteristic of the early settlements of these people. The community at large is primarily a farming one, but instead of living on their acreage, as is commonly the case in most other states, the owners have their houses in the nearby town. The buildings are greatly varied in point of structure. The oldest ones are built either of sun-dried bricks or of angular fragments of black basaltic lava. For nearly fifty years these people were without railroad connection, and during the greater part of that time were compelled to haul their supplies overland from Omaha and later from Salt Lake City. After the advent of the railroad, however, the houses were far better constructed so that today modern bungalows can be seen side by side with buildings of much more primitive type. The church and the schools constitute the best class of buildings in the town. Both are made of brick and reinforced concrete, and both are provided with conveniences seldom surpassed in centers of much larger population.

Elsinore is situated in Sevier Valley, 150 miles south of Salt Lake City, at an elevation of 5,335 feet above sea level. The valley at this

point is about five miles wide and is flanked on either side by sharp steep-sided plateaus which rise abruptly to a height of several hundred feet above the valley floor. Elsinore is situated within about one mile of the plateau on the west, while Monroe, a town of much the same size, occupies a similar position with reference to the plateau on the east.

Solid bedrock formations outcrop boldly in the adjacent plateaus but are completely covered by the wash comprising the valley proper. At places the valley attains a width of fully ten miles, while at others it narrows down to a mere canyon. The total length of Sevier Valley, including San Pete Valley, its structural continuation toward the north, slightly exceeds one hundred fifty miles. Sevier Valley drains toward the north and San Pete Valley toward the south, the combined waters of which cut a somewhat narrow opening through the Pavant Plateau on the west, and then after meandering for more than fifty miles, empty into Sevier Lake, the second largest body of saline water in Utah.

GENERAL GEOLOGY

A brief survey of certain aspects of local geological history will assist in studying the problem before us. It will be recalled that the Wasatch and Uinta Mountains were first of all elevated during the great Laramide revolution of late Cretaceous times. Then throughout the period of degradation and perhaps peneplanation that followed, vast areas in southern and southeastern Utah continued to be centers of sedimentation, largely continental and lacustrine. It was not until near the close of Tertiary times that these last-named areas were brought into marked topographic prominence. The second period of uplift differed from the first in at least two respects, it affected much wider areas and it produced great flat-topped plateaus instead of highly contorted mountains.

The second period of uplift also instituted a great series of north-south faults, incising not only the plateau country but the northern mountainous country as well. Aside from the faults associated with the basin ranges proper, there are at least half a dozen of these major fractures in Utah's great central highland, comprising the Wasatch Mountains at the north and the high plateaus at the south. This system of displacements begins far down on the Colorado platform and terminates close to the Idaho boundary. Most of the individual faults, however, are situated toward the south and are arranged in parallel overlapping positions.

At the extreme south and west is the Hurricane fault, with a length

of 200 miles and a maximum throw of 5,000 feet. Next to the east is the Sevier fault, thought to be about 225 miles long. At the far east is the Kiabab fault, reported as close to 300 miles long. The Wasatch fault at the northwest may properly be regarded as a northern continuation of the Hurricane. It has a length of approximately 150 miles and a maximum throw of at least 10,000 feet.

THE SEVIER FAULT

The Sevier fault begins just over the state line in Arizona, near Pipe Springs, and strikes in a northerly direction. It passes over a low divide in the Markagunt plateau at an elevation close to 9,000 feet. It continues in the same course throughout the entire length of Sevier and San Pete Valleys and terminates near the town of Fountain Green, practically 225 miles from its point of beginning.

Sevier Valley is primarily of structural origin, produced almost exclusively by faulting, here and there aided slightly by flexing. The steep-faced plateaus bounding it are gashed by numerous erosional canyons, but the valley proper is typically one of deposition rather than erosion, except only at two places, where the Sevier River has cut sharp V-shaped canyons through extrusions of igneous rock which have recently been thrown across its course. Deposition within the valley not only takes place at points where the tributary streams enter, but also at several places along the main course of the stream. The filling process is also aided by vast quantities of alluvium brought in by intermittent tributaries.

The major part of the fault movements giving rise to Sevier Valley seems to have occurred far back near the close of Tertiary times. Evidences of marked, recent faulting are practically lacking. The fact must not be overlooked, however, that the effects of slight movement in the valley wash would be quickly obliterated by the almost universal deposition which is taking place. On the other hand, there can be no doubt that the major part of the faulting dates back to remote times, as shown by the fact that when early lava flows worked their way down into the valley they found it in nearly its present form. Since that time the river has been able to cut deeply incised canyons into these barriers.

The Sevier fault is much more than a simple displacement. Its great length, in excess of 200 miles, suggests a complicated origin and structure. At various places along its strike the fault divides and subdivides in such a manner as to produce a series of parallel displacements. Step faults are not uncommon, as are also trough or graben

faults. Evidence seems to favor the conclusion that throughout the greater part of its course Sevier Valley owes its existence to rift displacements and related structures. The Sevier fault, therefore, should scarcely be thought of as confined to one plane, but more properly to a long narrow zone, here and there widening out to a few miles and at other places narrowing down to a single fracture.

Under such conditions it is to be expected that the throw will vary greatly from place to place, but the field work thus far done has not revealed any definite order of variation. Speaking only in very general terms, the throw appears to increase from each extremity of the fault toward the middle, and then as this point is approached the throw decreases and finally reaches nearly zero. This peculiar condition was pointed out by Dutton several years ago.

At the far south the fault is plainly downthrown on the *west* side, and at a similar position at the north the *east* wall is downthrown. Practically midway between these two extremes neither side gives evidence of marked displacement. Care must be taken, however, not to regard the fault as an ideal illustration of the pivotal or "scissors" type, yet when taken in the large it serves such a purpose very well.

The fact is of more than passing interest that the point of zero movement is situated not far from the town of Elsinore. The flanking plateaus in this vicinity are composed of Tertiary sediments capped by lava extrusions, and both are practically the same elevation, yet it will be recalled that at this point the valley is nearly five miles wide and affords evidence of rift or graben origin. It should be borne in mind, therefore, that while the plateaus on the east and west have suffered but little differential elevation, yet the block between them, now comprising the valley proper, has been depressed several hundred feet. Virtually all of the earthquakes that have occurred in the High Plateau country within the historic period of its occupancy, have been limited to within a very short distance of this "point of zero movement."

FORMER DISTURBANCES

No accurate record has been kept of former disturbances, although it appears from current reports that during the period since the country was first settled, at least two or three earthquakes of considerable violence have been experienced. The one about which most seems to be known occurred some twenty years ago and was sufficiently intense to topple a few chimneys and cause other damage of a similar nature.

PRELIMINARY TREMORS

Slight tremors were felt at irregular intervals for nearly two weeks prior to the principal disturbance on the morning of September 29, 1921. None of these, however, was sufficiently strong to cause any property damage, and most of them were felt only by individuals who were in houses, where they were most easily detected. A few of them were intense enough to waken people from their sleep.

THE THREE PRINCIPAL SHOCKS.

On September 29th at 7:12 a. m. a very strong shock was experienced at Elsinore and to a less extent in neighboring places. Judged on the basis of the Rossi-Forrel scale, it had an intensity of fully VIII. By some observers it is reported to have been preceded by a roaring noise; other observers say that the noise accompanied it, and still others that there was no noise except that occasioned by the falling of chimneys and other objects. There is a rather persistent opinion to the effect that the disturbance came from the southwest, although definite proof of this seems to be wanting. The shock was of sufficient intensity to injure all types of buildings. Scores of chimneys were thrown down, plaster fell from the ceilings, and walls were fractured and displaced.

No one seems to have kept a record of the time of duration of the disturbance. A young man informed the writer, however, that when the shock arrived he was in his back yard milking a cow, and even though he unceremoniously left the animal, the shock had not passed when he reached the bedside of his wife, who, with her babe, was in a rear room on the second floor of their home. From this source and others the writer has come to the conclusion that the disturbance must have lasted from seven to ten seconds.

At 7:30 p. m., on September 29th, or almost precisely twelve hours after the first destructive shock, another one of slightly less severity was experienced. A good many chimneys were thrown down and the general damage occasioned by the previous disturbance was materially increased. In the nearby town of Monroe this shock was more destructive than the one occurring twelve hours earlier. Opinions are again conflicting as to noises, direction of travel of earth waves and duration of the shock. It is generally agreed, however, that this disturbance did not last as long as the one in the morning. At Elsinore it seems to have had an intensity of VII and at Monroe of VII or probably VIII.

The writer arrived in the town of Elsinore twenty-four hours after the second earthquake. The people were everywhere in a state of high

excitement. Most of them were living out of doors and were in continual dread of probable recurrences. Among all of the people there was but one subject of conversation. That evening at the hotel, however, the guests seemed to have themselves pretty well in hand, and, in consequence, next morning the writer was greatly surprised to learn that during the night they had become apprehensive and taken up quarters out in the open. The writer had the hotel entirely to himself.

On the morning of October 1st, at 8:32, another very strong shock was experienced. The writer at the time was standing on a lawn in front of a two-story brick residence and across the street from a line of store buildings. For purposes of studying the effects of the disturbance he could not have had a more desirable position even if it had been selected with full knowledge of what was to come.

The shock arrived with absolutely no forewarnings and was as sharp as the blow of a giant hammer. There were no antecedent noises or rumblings, and the instant the effects of the single blow had passed, nature was as quiet and serene as if nothing had happened. The duration of the impact, therefore, can be measured only in terms of a small fraction of a second. Thus, the outstanding feature of this particular disturbance is the extreme suddenness with which it arrived and the short time it lasted. The blow was as quick and as short as the detonation of a cannon at a gunner's side. In fact the effect when standing in the open was not altogether unlike that experienced when a nearby field piece is discharged. The writer felt as if he had been struck by a sudden blow. There were no perceptible noises, however, except those occasioned by the resultant damage.

The effect of the blow in shaking trees, buildings, and other objects had almost entirely passed at the close of one second. During this brief period all moveable objects were in a state of violent agitation. The writer directed his attention first of all to some nearby trees, then to the residence not more than thirty feet away, and finally to the line of buildings across the street. The trees were shaken as violently as a school boy shakes a limb when stealing his neighbor's fruit.

The effect upon the nearby brick buildings was intensely interesting. The motion of the various walls were not synchronous in the same direction, but rather in opposite directions, in and out, as if the building were inflated and deflated in quick succession. While, of course, the extent of the movement was not great, yet it was sufficient to be easily noticeable, and probably reached a maximum of two to four inches. Furthermore, every brick appeared to be loosened from contiguous ones. Until



Fig. 3. At the side of the public school building where the children usually play.



Fig. 4. Another illustration of a poorly constructed old building.



Fig. 5. Chimney twisted by torsional movement. This new brick residence was otherwise badly damaged.



Fig. 6. Two bricks were plucked from this chimney, leaving the mortar in place.

these phenomena were actually observed the writer did not believe that a building could be subjected to such violent disturbance and remain intact. The entire structure looked as if it would tumble into a heap at any instant, and yet it suffered nothing more than the loss of some plaster and a chimney or two. The close proximity of the writer to this building was of great advantage in studying it, for when he directed his attention to others across the street, none of the details of the movement could be seen.

The noise arising from creaking houses and falling chimneys came in from every part of the town, and sounded not unlike the clattering of many horses feet on a wooden floor. Instantly the cries of hysterical women and frightened children followed, and simultaneously they rushed from their homes out into the streets. The utter helplessness of people during earthquake disturbances is perhaps not equaled at the time of any other disaster, for even at times of floods or wreckage at sea there is usually some hope for escape, but with earthquakes no one can stay their coming or foretell the time of their arrival. This condition was brought home to the writer by the manner in which these people wandered from place to place in abject fear of possible recurrences. Then again, on such occasions the majority of people lose their self-control and rush about without thought or judgment.

The earthquake arrived at a time when the country at large was very dry. The dust arising from the shock was fully as dense as that occasioned by a sudden wind storm. About a hundred yards from where the writer stood a store front was projected violently into the street, so that in that particular direction vision was completely obscured for fully a half minute.

Measured in terms of the Rossi-Forrel scale, this disturbance had an estimated intensity of VIII or just about the same as the one of two days earlier. The former disturbance, however, wrought considerably more damage, but this is probably explained by the fact that it lasted longer, rather than that it was actually more violent.

A large number of minor vibrations were felt for about two weeks after the last of the major disturbances, and then for several weeks they entirely disappeared. But just now (December 20th) while the writer is arranging his notes, word has been received from the field of further tremors. Mr. Harold Anderson, principal of the schools of Elsinore, has been kind enough to keep careful records and forward them to the writer at Salt Lake City.

LOCUS OF THE DISTURBANCES

It will be recalled that Elsinore is situated close to the west side of a flat-bottomed valley, at this point about five miles wide. The town of Monroe is situated three to four miles southeast of Elsinore and near the east side of the valley. Richfield, the county seat, is seven miles down the valley toward the north, and Joseph is an equal distance to the south.

The disturbance at 7:12 a. m., September 29th, affected a wider range of country and did more damage than either of the two that followed. It was strongest at Elsinore. It did considerable damage, however, at Monroe and shattered a few chimneys at both Joseph and Richfield. Beyond these points it seems to have been scarcely more than noticeable. It is reported by cattlemen to have been felt in a mountain cabin some five miles southwest of Elsinore.

The second major disturbance threw down a few chimneys at Elsinore, but was much more destructive at Monroe than was the first one twelve hours earlier. It was felt only slightly at Richfield and Joseph, each seven miles distant.

Of the three major disturbances the one occurring at 8:32 on the morning of October 1st appears to have been the most highly localized. It was very severe at Elsinore but constituted scarcely more than a well-defined tremor in each of the other towns, and in them was attended by no property damage, except a little at Monroe. At Elsinore, however, this shock caused much loss to property and undoubtedly would have equaled that of two days earlier had the disturbance lasted as long.

In no case, therefore, were any of the earthquakes felt over a wide range of country. People living as little as twenty-five miles distant did not know of the occurrences except as later informed. These facts seem to prove that the point of origin could not have been far beneath the surface and was on one or more of the fault planes giving rise to the Sevier rift.

ATTENDANT PHENOMENA

A number of interesting phenomena were produced by the earthquake. At several points along the faces of the abrupt plateaus, boulders are reported to have been loosened from their bearings and to have caused great clouds of dust as they rolled down to lower levels. This statement is substantiated by evidence from a large number of people. The writer is informed that the falling of boulders was particularly noticeable at Monroe during the first and second shocks, and immediately east of Joseph also during the second shock.

Along the east margin of the valley at Monroe and also at Joseph are a number of hot springs, the water of which in certain cases is heavily charged with red oxide of iron. On at least two occasions the water from these springs is said to have become almost blood red immediately following the earthquake. The report was verified by the writer in finding nearly one-fourth of an inch of iron oxide on the floor of a swimming pool into which the water was flowing. An examination of the spring showed quantities of flocculent iron clinging loosely to the walls of the cavity from which the water was issuing. Evidently the shocks had been sufficiently violent to dislodge similar material and thus permit it to be carried up to the surface.

The writer has not done sufficient field work to satisfy himself as to whether the water of these springs comes from one of the fault planes or whether it issues from a nearby recent lava flow. The fact that similar springs are known to have existed on the Sevier fissure at Redmond some thirty miles to the north, is suggestive of a like origin, although there are other factors that appear to negate this conclusion.

DESTRUCTIVE EFFECTS

The three major earthquakes arranged in the order of their destructive effects are as follows:

- | | |
|--------------------------------|--------------------|
| 1. September 29, at 7:12 a. m. | } Greatest damage. |
| 2. October 1, at 8:32 a. m. | |
| 3. September 29, at 7:30 p. m. | Least damage. |

It will be well to discuss the destructive effects collectively, except in cases noted. Measured in terms of actual cost, the greatest damage done to any single building was at the public school house. The structure is a new two-story brick building, about fifty by sixty feet in the front, with a one-story thirty by sixty gymnasium behind. A firewall some two to five feet high, constructed around three sides of the main building and two sides of the gymnasium, was almost entirely thrown down by the first shock. Several pilasters mounted on the front of the building were also dislodged. In the gymnasium the ceiling was torn loose from the walls in such a manner as to admit daylight. It is very fortunate that the earthquake did not take place at a time when the children were on the grounds, otherwise many lives might have been lost. In the aggregate tons of material were plunged to the ground where the children ordinarily play.

Close to the new school house is an older one constructed of rec-

tangular blocks of rock. This building was not seriously impaired except on the second floor, where several yards of plaster fell to the pupils' desks. The walls were also pulled apart from the ceiling.

Perhaps the most expensive building in the town is the Mormon church house, a handsome brick structure of modern design and construction. The only damage to be seen is the cracking of some of the walls and the twisting of two small pilasters mounted near the tower.

The front of one of the store buildings was cracked badly by the first shock and thrown down entirely by the third. The building was also otherwise damaged to such an extent that it will have to be razed.

The greatest aggregate damage, however, was done to the residences, of which perhaps fully one-half seriously suffered. Probably fifty per cent of the chimneys in the town were thrown to the ground, and practically all of the remaining ones were rendered unfit for further use. To some extent or other plaster was shaken from the ceilings of nearly every residence. In a few cases where chimneys broke off beneath the roof, they went thundering through the ceilings and directly into occupied rooms. Most of the chimneys, however, fell on to the roofs and then rolled to the ground. In scores of homes pictures were torn from the walls and bric-a-brac was strewn about the floors. In numerous cases walls were badly cracked and thrown out of alignment. Ten to twelve residences were rendered unfit for further occupancy.

A number of curious things were observed, especially in connection with chimneys. One chimney was twisted by a torsional movement through an angle of more than forty-five degrees. In another case two bricks were extracted from the side of a chimney without even disturbing the mortar that enclosed them. They were thrown sixteen feet clear of the building. In still another case two sides of a chimney were popped out and yet it remained standing.

TYPES OF BUILDINGS MOST AFFECTED

As noted elsewhere, some of the buildings in both Elsinore and Monroe are of very primitive construction, being made either of sun-dried bricks or of angular fragments of stone. The more modern types are perhaps evenly divided between brick and lumber. The public buildings are principally brick and cement.

The buildings that suffered most were those made of angular fragments of stone. Next came those of sun-dried bricks, then the brick houses and finally those constructed principally of lumber. The last type suffered very little except from falling plaster and toppling chimneys.

SUMMARY AND CONCLUSION

The towns of Elsinore and Monroe are situated near the pivot of the great Sevier rift. Intense movements have occurred along this zone in somewhat recent geological times. The earthquakes of September 29 and October 1, 1921, were undoubtedly initiated by movements on one or more of the various planes of this fault zone. While it is undoubtedly true that the growth of the High Plateaus has practically ceased, and, therefore, that displacements on the Sevier fault are largely past, yet further recurrences are by no means improbable.

LIST OF SHOCKS

Elsinore, Utah, 1921

Sept. 12,	3:18 a. m.	Awakened people from sleep, slight damage.
Sept. 12,	3:32 a. m.	
Sept. 12,	6:27 a. m.	Awakened people from their sleep.
Sept. 18,	8:00 p. m.	Slight tremor.
Sept. 28,		Various slight tremors during night.
Sept. 29,	7:12 a. m.	Very strong shock, intensity of VIII.
Sept. 29,		Twenty-three tremors reported during day.
Sept. 29,	7:30 p. m.	Strong shock, intensity of VII.
Sept. 30,	7:00 p. m.	Slight tremor.
Oct. 1,	8:32 a. m.	Very strong shock, intensity of VIII.
Oct. 1,	10:30 a. m.	Slight tremor.
Oct. 1,	6:05 p. m.	Slight tremor.
Oct. 3,	8:00 p. m.	Slight tremor.
Oct. 4,	10:25 a. m.	Slight tremor.
Oct. 8,	1:30 p. m.	Slight tremor.
Oct. 10,	1:30 a. m.	Very slight tremor.
Oct. 10,	2:45 a. m.	Very slight tremor.
Oct. 15,	4:15 a. m.	Barely noticeable.
Oct. 15,	5:27 a. m.	Distinct, observers heard it approaching, duration five seconds.
Dec. 20,	3:40 a. m.	Slight tremor.
Dec. 20,	3:47 a. m.	Slightly harder than previous one.
Dec. 20,	4:40 a. m.	Slight tremor.
Dec. 20,	5:40 a. m.	Slight tremor.
Dec. 20,	6:30 a. m.	Slight tremor.
Dec. 20,	8:10 a. m.	Most severe of December series, no damage.
Dec. 20,	8:40 a. m.	Slight tremor.
Dec. 20,	3:20 p. m.	Distinct.

UNIVERSITY OF UTAH

SOME RELATIONS OF EARTHQUAKES TO GEOLOGIC STRUCTURE IN THE EAST INDIAN ARCHIPELAGO

By H. A. BROUWER

Although the records of earthquakes go back some centuries for the oldest centers of colonization in the East Indian Archipelago, many regions are almost unknown as regards their seismicity, and the material is insufficient for a comprehensive earthquake history, even if we only consider the last half of the nineteenth and the beginning of the twentieth century, during which the data relating to earthquakes have been collected in catalogues, while in 1898 the first seismograph for the registration of microseisms, and in 1908 a Wiechert astatic pendulum seismometer came into operation at Batavia.

A valuable earthquake catalogue for the archipelago, of which the first part has been published, was prepared by Wichmann.¹ This first part contains data about all known earthquakes up to the year 1857.

Although many anomalies result from lack of information, as can be seen on the maps of Montessus de Ballore, still the available data justify some conclusions about the distribution of unstable regions in connection with the crustal movements, which often are of different character for neighboring parts of the archipelago.

It is a well-known fact that the earthquake zones of the globe in a broad way may be traced along the mountain ranges of Tertiary age. The East Indian Archipelago is situated at the junction of the Mediterranean range (Alps, Himalaya, etc.) and the Circum-pacific range and is one of the regions of great seismicity. But earthquakes do not occur where mountains have been growing in Tertiary time, *but where they are still growing now*, and therefore it is of great importance for the study of earthquake regions in this territory that the movable area of the latest geological period is only confined to a part of the original Mesozoic geosyncline.

REGIONS OF UNIFORM AND OF COMPLICATED SUBMARINE TOPOGRAPHY.

There exists a striking difference between the western and a great part of the eastern portion of the East Indian Archipelago. Sumatra, Java, and Borneo would form one mass of land with Cambodja, and Siam and Australia would form one mass of land with the Aru Islands, New

¹ A. Wichmann, "Die Erdbeben des Indischen Archipels bis zum Jahre 1857," *Verh. Kon. Akad. v. Wetensch. Amsterdam* (2e sectie), 20, 4, 1918.

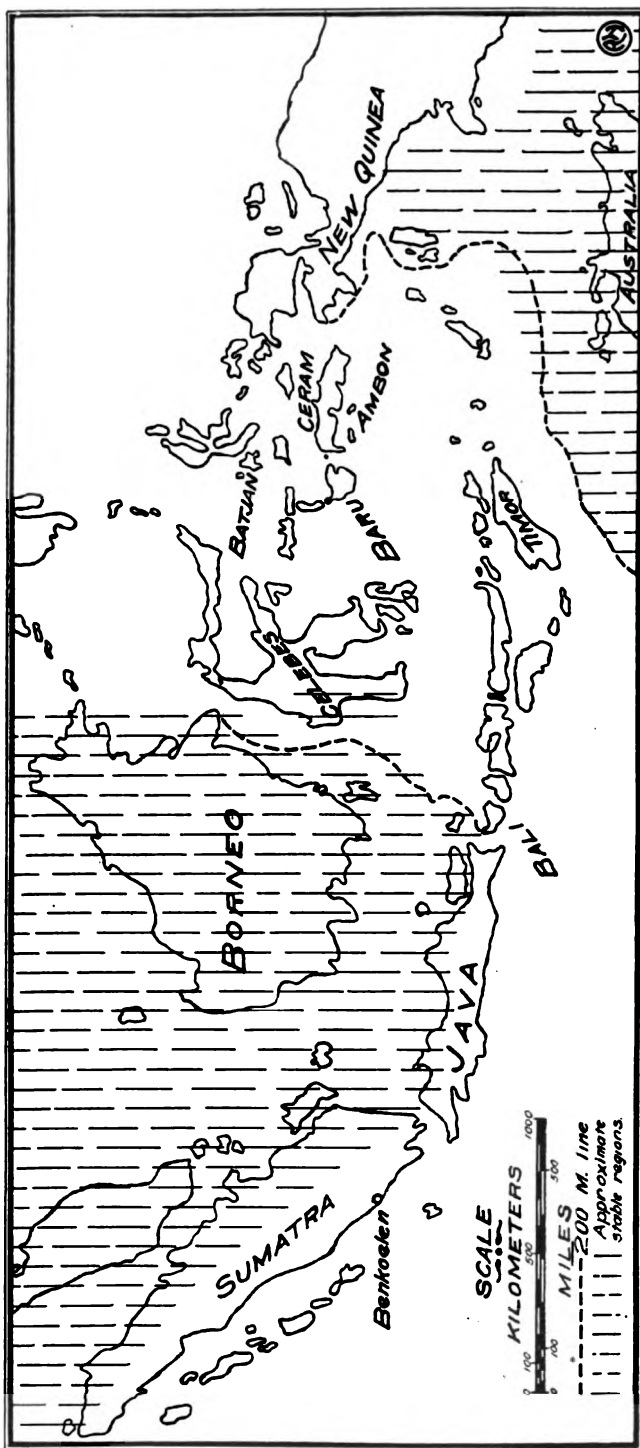


Fig. 1. Stable and unstable regions in the East Indian archipelago. (Schematic representation.)

Guinea and the northeastern Moluccas, if the sea-level were to subside 200 meters. These regions show a gentle topography both of land and sea-bottom, and in the latest geological period important crustal movements took place in the parts adjoining the Indian and Pacific Oceans only.

Between the large western islands of the archipelago and the Australia-New Guinea region lies an area in which deep sea-basins alternate with upheaved islands. Depths greater than 5000 meters occur in the Banda Sea and the Flores Sea, whereas to the west of the Kei Islands the greatest depth, 6,505 meters, has been found. The region of the curving rows of islands around the Banda Sea presents an aspect similar to that which parts of the Mediterranean geosyncline must have presented at some time in the Mesozoic period.

The East Indian Archipelago consists of a stable and an unstable part, one with an exceptionally uniform and undisturbed submarine topography and another with a very complicated structure. The part of the archipelago adjoining the Indian Ocean (southwestern part of Sumatra and southern part of Java) belongs to the unstable region.²

EARTHQUAKES AND VOLCANOES

Where mountains are growing earthquakes will occur, but where mountains are growing, active volcanoes are often entirely lacking, and this independence of seismicity and volcanicity is also very striking in the East Indian Archipelago. The row of islands to the west of Sumatra is known for its frequent and intense earthquakes, but volcanoes are lacking, and the same holds for islands of the Timor-Ceram row. The earth blocks can move during long periods, without squeezing out the molten magma along the fissures, or an existing volcanic vent may be stopped up and lava is no longer exuded at the surface. In the youngest geological period the unstable belts occupy a much larger surface than the volcanic belts, but volcanic rocks cover a vast area in the unstable regions without active volcanoes. In the regions with active volcanoes the earthquakes show the same independence of volcanic activity. Besides crustal movements there are many other causes which control the possi-

² H. A. Brouwer, "The Major Tectonic Features of the Dutch East Indies," *Journ. Wash. Acad. of Science*, 1922, No. 7 (published after this paper had been concluded.) For an extensive summary of the geology of the unstable eastern part of the archipelago comp.: H. A. Brouwer, "Geologisch Overzicht van het oostelijk gedeelte van den Oost-Indischen Archipel," *Jaarb. v. h. Mijnwezen in Ned. Indië, Verh.* 1917, 2, 147-452.

bility of volcanic eruptions, and the continuance of an eruption depends on victory in the struggle with cold.³

The mutual relationship of volcanic activity and crustal movements is illustrated by the rows of islands in the southeastern part of the archipelago, where it appears that during the recent crustal movements in the outer row of islands around the Banda Sea the magma has not reached the earth's surface, while the inner row is characterized by a great number of volcanoes on top of the geanticline. It is of importance that the active volcanoes are also missing in the inner row, just where the rows approach each other most, i. e., to the north of Timor. Moreover it is of importance, that, starting from the island of Wetter (to the north of Timor), where the two curving rows of islands are closest to each other, the volcanoes of the inner row are extinct at a later period according as they are farther removed from Wetter.⁴ Evidently there is an exact relationship between the divergence of the two rows of islands and a more prolonged volcanic action consequent on a progressing distance from the front of the stable Australian submarine bank. It is a well-known fact that the crustal movements are highly influenced by the form of and the distance from stable regions in the neighborhood, and it would seem legitimate to assume that the crustal movements, causing the earthquakes in the two rows of islands and in the adjoining deep sea-basins, have been of different character at the same time for different places, and have varied also at the same place during the evolution of the geanticlines and geosynclines in the youngest geological period. If more or less horizontal movements take place, they will give rise to an increase in thickness of the crust and an existing volcanic vent may be stopped up; if these movements take place from the beginning there is no possibility for an exit of the magma on the top of the moving geanticline. For details about this question, we refer to an earlier paper, cited above.

From these facts it follows that a mutual relationship of volcanic eruptions and earthquakes does not exist (we except the shocks, which always accompany violent volcanic outbursts). That earthquake zones often coincide with volcanic zones is only true in a broad sense; when considered in detail we can state only that for both phenomena there is a relation to successive movements of the earth's crust.

³ R. A. Daly, "Igneous Rocks and Their Origin," p. 251, 1914.

⁴ H. A. Brouwer, "On the Non-Existence of Active Volcanoes Between Pantar and Dammer (East Indian Archipelago), in Connection with the Tectonic Movements in This Region," *Proc. Kon. Akad. v. Wet.* Amsterdam, 21, 795-802.

Id. "Über Gebirgsbildung und Vulkanismus in den Molukken," *Geol. Rundsch.*, p. 197, 1917.

THE SUBMARINE POSITION OF THE EPICENTERS IN CONNECTION WITH
THE HORIZONTAL MOVEMENT OF GEANTICLINES

One of the most interesting results of recent seismological research in the East Indian Archipelago is *that the epicenters lie mostly under water*. In Japan and many other regions this fact is well known, and strong shocks often cause tsunamis or earthquake sea-waves and at times devastate the pleistoseistic area in the neighboring coastal regions.⁵ The epicenters of the earthquakes in the neighborhood of western Java have been calculated by Visser⁶ for the period from January, 1909, to August 1, 1919, during which time a Wiechert seismograph was in operation at Batavia, and more particularly from August 1, 1911, the date since which a seismograph has been in operation at Malabar (Preanger Regencies, 7° 13', S. L.; 107° 37', E. L.). The result of his calculations is that the epicenters of the great majority of the earthquakes in western Java lie on the submarine slopes to the south of Java and southern Sumatra. Visser has extended his calculations to the whole archipelago and informed me that the same rule is applicable, so far as the 123 calculated epicenters of the heavier shocks are concerned.

These results are quite different from those which are mentioned by Montessus de Ballore,⁷ who supposed that a great many epicenters were lying on the islands. For Java he speaks of a nearly uniform distribution of the epicenters on the island, and he thought that the southern coast has been relatively stable in recent time.

If we look for an explanation of the remarkable submarine position of the epicenters of the last twelve years, it seems possible that there is a connection between this position and the character of movement of the geanticline. If we suppose that the movement of the submarine slope is much stronger than that of the other parts of the geanticline, it may seem that, in a certain space of time, only these submarine parts are moving. Stronger movements on the submarine slopes can be explained if the rows of islands tend to move in a horizontal direction. In some recent

⁵ B. Koto, "Morphological Summary of Japan and Korea, III," *Journ. of Geol. Soc. of Tokio*, 22, 171.

⁶ S. W. Visser, "Aardbevingen in en om West-Java," *Natuurk. Tijdschr. v. Ned. Indië*, 79, 181, 1919. After this paper had been completed an article of Visser was published in which the distribution of earthquakes in the archipelago is discussed. Cf. "On the Distribution of Earthquakes in the Netherlands East Indian Archipelago, 1909-1919," *Vehr. No. 7, Von. Magn. en Meteor. Observ.*, Batavia, 1921.

⁷ F. de Montessus de Ballore, "Les tremblements de terre," 1906.

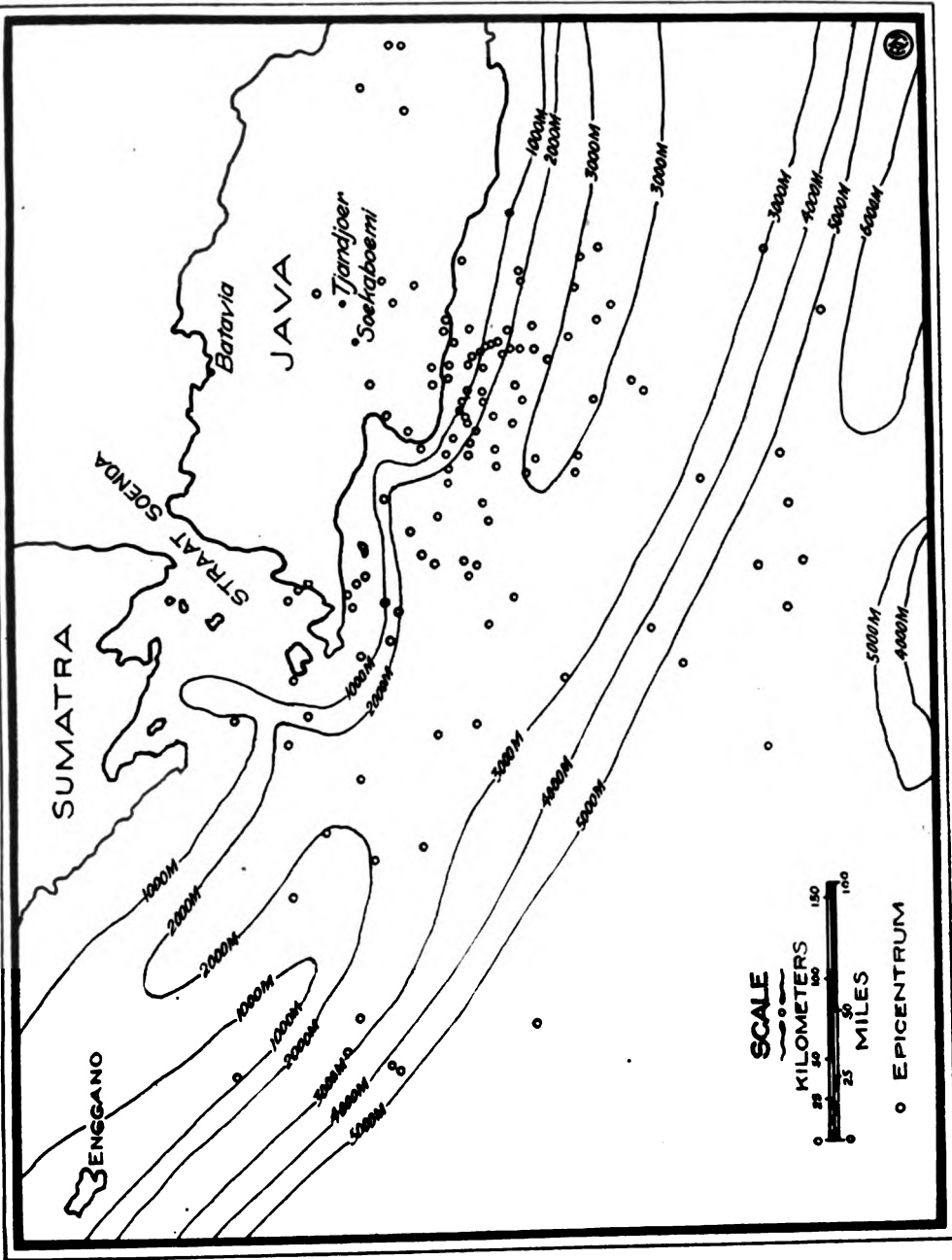


Fig. 2. Epicenters near West Java and South Sumatra. (After S. W. Vissar.)

publications I have pointed out that from the shape of different rows of islands in the East Indian Archipelago it may be concluded that, besides movement in a vertical direction, they may move also largely in a horizontal direction. Asymmetrical reef-caps⁸ coincide with marked outward bends of the rows of islands, while the faults and fractures near the surface demonstrate differences of velocity in a horizontal direction between adjacent parts of the moving geanticlines.⁹ If the forces which cause the movement are deep-seated and the crust near the surface does not undergo the direct influence of the compressional and tensional stress, the displacements near the surface will be the result of the more plastic deformation at greater depth. If important horizontal movements take place in the zone of more plastic deformation, the superficial parts above sea-level may move with much less velocity.

The horizontal movements may take place along more or less horizontal planes and cause the formation of overthrusts, or along more or less vertical transverse planes. An extension of the geanticlinal axis is obtained by gaping fractures or by movements along fault-planes, which must be inclined to the geanticlinal axis. Shortening is possible by faulting along fault-planes, which are not vertical to the geanticlinal axis. From the above statements it follows that there must be a connection between the position of the epicenters and the character of the geanticlinal movement *in space*. This movement can be broadly described by indicating how the horizontal and vertical projections of the geanticlinal axis and how the section of the surface of the geanticline with a vertical plane at right angles to the geanticlinal axis are moving. If we suppose that at the beginning of the movement the geanticlinal axis is a straight line, then in general the vertical as well as the horizontal projection will have obtained a curved form at a following stage of movement. Of the numerous possible deformations we will consider two general types only. The original geanticlinal axis will not be the new axis in a following stage of movement, but for an approximate judgment the figures 3 and 4 are applicable.

Earthquakes Along Longitudinal Tectonic Lines.—If the geanticlinal axis $A_1a_1B_1$ of figure 3 tends to be distorted to $A_2a_2B_2$ strong movements will take place on the present islands and in the present sea-basins. If the axis $A_1a_1B_1$ of figure 4 tends to be distorted to $A_2a_2B_2$

⁸ H. A. Brouwer, "On Reef Caps," *Proc. Kon. Akad. v. Wetsch*, Amsterdam, 21, 816.

⁹ H. A. Brouwer, "The Horizontal Movements of Geanticlines and the Fractures Near Their Surface," *Journ. of Geol.*, pp. 560-577, 1921.

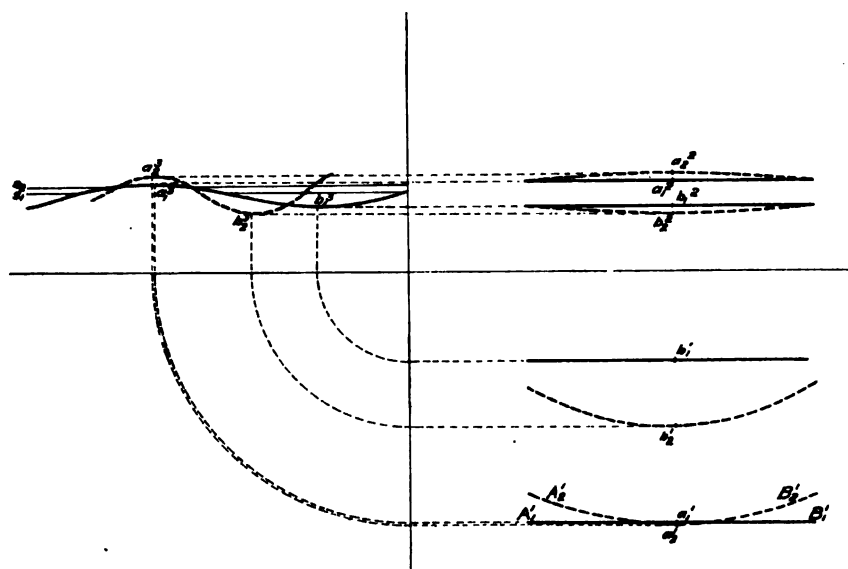


Fig. 3. Vertical movement of the geanticlinal and horizontal movement of the geosynclinal axes with strong velocity differences for neighboring parts of the horizontal projection. S_1 and S_2 sea-level.

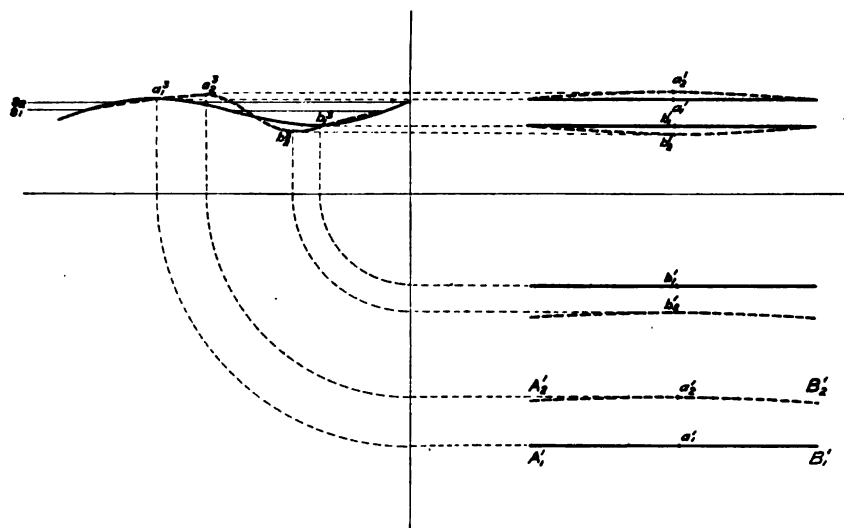


Fig. 4. Horizontal movement of the geanticlinal and geosynclinal axes with small velocity differences for neighboring parts of the horizontal projection. S_1 and S_2 sea-level.

strong movements will take place on the slope of the present islands and in the adjoining sea-basins.

It will depend on the height of the sea-level (S_1 or S_2) whether the epicenters of most earthquakes will be situated below sea-level or partly on the moving slope of the islands themselves.

Earthquake water-waves are rather infrequent along the south coast of Java, while they are more numerous to the west of Sumatra. The great tsunamis which so often devastate the shores of Japan are brought in connection with movements in or in the neighborhood of the near-lying Tuscarora deep, while the California earthquake of 1906 was not followed by tsunamis. The movements on shore in the latter case consisted more largely of adjustments within the horizontal plane,¹⁰ and we are also led to infer that the recent movements along the south coast of Java are not characterized especially by vertical adjustments.

Examples in the archipelago of earthquakes along longitudinal tectonic lines are the Benkoelen earthquake of 1914 and the Ceram earthquake and sea-quake of 1899, which will be described below. If the earth's crust is moving along some longitudinal tectonic lines only, the earthquakes may be of great extent but relatively few in number, because they may be easily propagated over long distances parallel to the longer axis of the islands.

Earthquakes Along Transverse Tectonic Lines.—In the figures 3 and 4 the horizontal as well as the vertical projections of the geanticlinal axis tend to obtain a curved form. In general the distortion of the vertical projection will not be important, if we except the case in which a strong compression is acting in the direction of the geanticlinal axis, from which would result a deformation to transverse folds normal to the geanticlinal axis. The deformation of the horizontal projection may be considerable. In another paper¹¹ we have pointed out that considerable transverse fractures near the surface of some geanticlines in the East Indian Archipelago coincide with bending-points of the horizontal projection of the geanticlinal axis. The straits between West-Timor and Rotti, between East-Timor and Letti and between Ceram and Buru coincide with these bending-points. The depth of the straits, sometimes considerable, and the characteristics of the upheaved coral reefs on both sides, point to the existence of transverse gaping fractures near the surface, which were formed by a movement with a component normal to the fracture-plane. They are the surface-expression of differences in

¹⁰ W. H. Hobbs, "Earthquakes," p. 255, 1908.

¹¹ H. A. Brouwer, "The Horizontal Movements of Geanticlines," etc., *loc. cit.*

velocity for neighboring points of the horizontal projection of the geanticlinal axis. At greater depth these differences in velocity will cause horizontal movements along transverse fault-planes, and these movements of an earlier stage of evolution of the geanticlines will gradually be uncovered by erosion and may now be visible at the earth's surface. In the row of islands Sumatra- Java-Flores, *e. g.*, numerous transverse faults of an earlier stage of evolution occur near Strait-Sunda.¹² In West Java nearly always the western portion is moved toward the south.

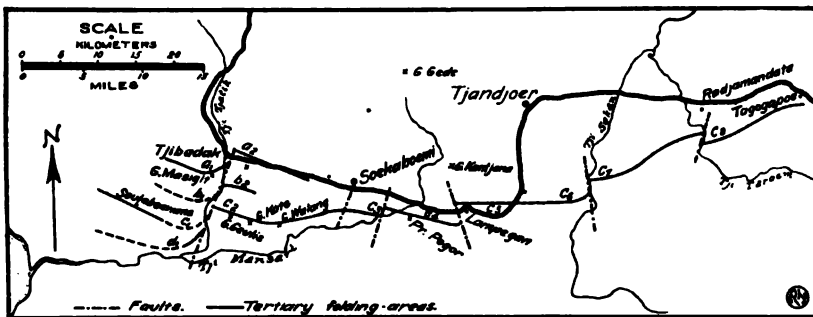


Fig. 5. Transverse faults in West Java (after L. J. C. van Es). Along each fault the western part has been pushed more to the south.

Along the fault-plane of the Tji-Tjatih near Sukabumi the displacement amounts to 4 km., at the very least, and the result of the movements of different ages is that the western part of Java has been moved several tens of kilometers toward the south in regard to south Sumatra. In this region a part of the epicenters follows transverse fault-lines as those in the southwestern prolongation of Strait-Sunda.

If the earth's crust is moving *with velocity-differences* between adjacent parts of the geanticline along transverse tectonic lines, the earthquakes,—compared with those along longitudinal lines,—may be very frequent but more of local origin.

In our paper on the horizontal movement of geanticlines (*loc. cit.*) we have pointed out that older folds often are cut off by the present coast-lines. This may in part be the result of a change in the direction of the compressive forces, but it can exclusively be the result of differ-

³ R. D. M. Verbeek et R. Fennema, "Description géologique de Java et Madura." L. J. C. van Es, "Geologische Overzichtskaart van den Ned. Oost-Indischen archipel," Toelichting bij Blad, XV, *Jaarb. v. h. Mijnwezen Verh.*, 2, 132, 1916; and *Jaarb. v. h. Mijnw.*, 2, 1917 (map).

ences between the horizontal component of the rate of movement for adjacent parts of the geanticline. From these same differences result frequent movements along transverse fractures and thus we may expect to find *earthquakes along transverse tectonic lines in regions where older folds are cut off by the present coast-lines*. A good example is found in Japan, where, in the southern part, though not exclusively, the earthquakes are of longitudinal nature, while the northern part, where the older folds of the Abukuma and Kitakami mountains are oblique to the present coast-lines, is a region of mainly transverse earthquakes with high frequency.¹³

Longitudinal and Tranverse Tectonic Lines Combined.—The intersections of seismotectonic lines are points of high seismicity. If strong movements on the slope of the islands and in the adjoining sea-basins result from important horizontal movements of the geanticlines, the greatest seismicity may be expected at those places, where differences in velocity of the horizontal movements exist, *e. g.*, near the bending-points of the horizontal projection. At those places longitudinal and transverse seismotectonic lines will intersect.

The region in the neighborhood of Strait Sunda between Sumatra and Java is one example of this kind, and the region in the neighborhood of Strait Manipa between Ceram and Buru is another one; but the exact position of the epicenters in the latter region is but little known. If a seismograph should be established in the eastern part of the archipelago, for instance on the island of Ambon, this would much advance our knowledge of the relation between earthquakes and geologic structure.

A striking irregularity of the geanticline to the north of the Banda Sea is the narrow Manipa Strait, nearly 5,000 meters deep, near the bending-point of the horizontal projection of the geanticlinal axis between Ceram and Buru, and near a bending-point of the Tertiary mountain-range of this region in an earlier stage of evolution. This strait and the irregular coast-lines in West-Ceram point to the existence of numerous, more or less transverse fractures, which are the surface-expression of velocity differences of similar horizontal movements as those from which resulted the overthrusts in Tertiary time, that now are uncovered by erosion on Ceram and Buru. (*Cf.* "The Horizontal Movements," etc., *loc. cit.*). One of the recent heavy earthquakes in this region, the Ambon earthquake of 1898, which will be described below, was characterized by

¹³ B. Koto, "Morphological Summary of Japan and Korea, III," *Journ. Geol. Soc. of Tokyo*, 22, 169.

shocks along seismotectonic lines transversal to the longer axis of the island.

DESCRIPTION OF SOME RECENT EARTHQUAKES

In order to give an idea of the relation of earthquakes to geologic structure and to faults and fractures in the East Indian Archipelago some of the better known earthquakes of recent time will be briefly described.

The Ambon Earthquake of 1898.—From all recorded earthquakes on this island some are better known, and from the description Verbeek¹⁴ concluded that two types can be distinguished:

1. Heavy shocks along seismotectonic lines transversal to the longer axis of the island.
2. Shocks of lower intensity with their epicenters not on the island itself, but on other islands in the neighborhood, as Haruku, Saparua and Ceram.

Volcanoes are entirely lacking.

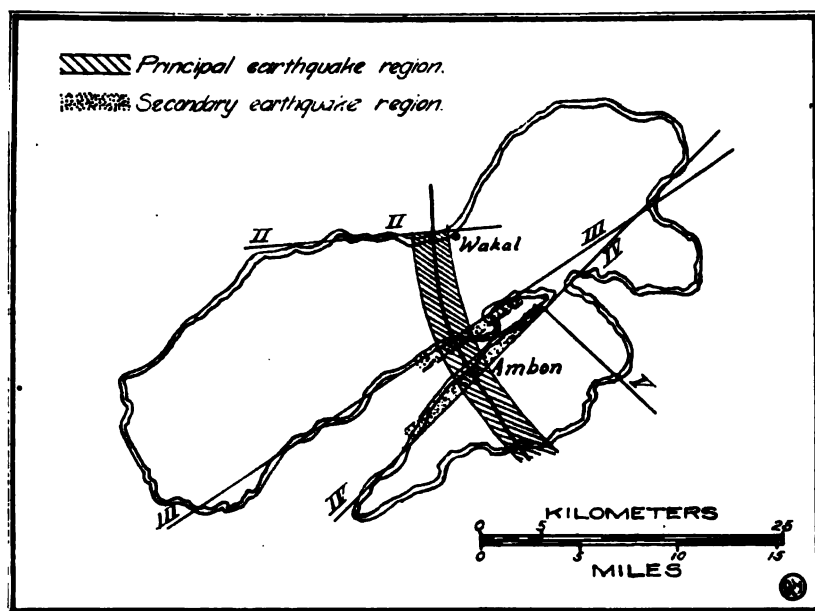


Fig. 6. The Island of Ambon (after R. D. M. Verbeek). I to V, faults.

¹⁴R. D. M. Verbeek, "Geologische Beschrijving van Ambon," *Jaarb. v. h. Mijnwezen, Wet. Ged.*, pp. 264-308, 1905.

The earthquake of 1898 belongs to the first type. The heavy shock on January 6th was preceded by some weak vertical ones, felt about one hour before. The pleistoseist region has the form of a long narrow strip, directed NNW-SSE, and *coincides with a fault-line*, which crosses the island in the same direction. From January 6th to 31st shocks were felt nearly every day, and until April 27th the movements continued, with eighteen earthquake days in February, thirteen in March and nine in April.

A vertical displacement along the fault-plane has not been observed at the surface, nor have horizontal shiftings been reported, but the movement was principally a horizontal one, while the vertical movements increased toward the north coast of the island. The heavy shock on January 6th was felt at Ambon, at the islands to the east (Haruku, Saparua), at the western part of the south coast of Ceram and also at the north coast of the latter island. Earthquake water-waves did not occur along the coasts of the island, while in the Ambon Bay only a slight movement of the water was observed. It is of interest to mention that, except the primary movements with a direction NNW-SSE, there have also been felt slight movements with a direction nearly perpendicular to the primary one, which probably correspond to other fault-lines which are known along the coasts of the island.

Another heavy earthquake with about the same direction and connected with water-waves at the north coast is that of February 17, 1674. It is of interest that many of the Ambon earthquakes have been felt at the same time on the neighboring islands, belonging to the same Buru-Ceram geanticline, but that they are often not felt on the neighboring island of Banda, which belongs to another geanticline, which is separated by a deep sea-basin from the Buru-Ceram geanticline.

The Bali Earthquake of 1917.—One of the heaviest earthquakes ever felt on this island was that of January 21, 1917. Observations made by Kemmerling¹⁵ shortly afterward showed that the shocks came from the SSE, that the earthquake was observed on the whole island Bali, the eastern part of Java and on Lombok, but that it was particularly strong in the narrow southern plain of Bali. The greatest disasters occurred in the southern and western part of the volcanic Batur Mountain. While in the southern plain horizontal movements were observed, in the Batur Mountain vertical shocks predominated. In the northern part of the island both horizontal and vertical movements were felt.

¹⁵ G. L. L. Kemmerling, "De aardbeving van Bali op 21 Januari, 1917," *Jaarb. v. h. Mijneezn, Verh.* 1, 1, 1917.

The active Batur volcano did not show any more intensive activity. The observatory at Batavia calculated the epicenter at a distance of 1190 km. in a direction E. 19° S., that is, to the south of the island Sumbawa, but Kemmerling supposes that a more exact place for the epicenter is found at the intersection of the line of shock direction, from Bali to the SSE, and the direction E. 19° S. from Batavia. The cause of the earthquake is supposed to be a movement which took place in the deep sea-basin to the south of Bali.

If we compare the different historical data about earthquakes on Bali we find that in certain villages shocks have been repeatedly felt, while other parts of the island remained immune at the same time. This points to the existence of lines of shock on the island itself, and a glance at a map makes it highly probable that many fault-lines must exist on the island and near the coasts. The direction of the twenty-seven heavier earthquake shocks since 1854 which damaged the island of Bali,¹⁵ was as follows:

from	S	to	N	3
from	SE	to	NW	7
from	E	to	W	7
from	SW	to	NE	1
from	N	to	S	1
from	W	to	E	3
from	NE	to	SW	5

From this, in connection with the localization of different earthquakes to different places, it is evident that movements in the deep sea-basin to the south of the island can have been the cause of many earthquakes, but that also movements took place along other tectonic lines, which partly cross the island itself and partly cut off the coasts.

The Benkoelen Earthquake of 1914.—Along the west coast of Sumatra earthquakes are frequent, sometimes they are of great intensity. The row of islands to the west is also characterized by a high seismicity; disastrous water-waves are mentioned and many of the shocks have their epicenters in the sea-basin, which separate Sumatra from the row of islands and adjoin these islands to the west. The Benkoelen earthquake of 1914¹⁶ was of tectonic origin; the pleistoseist region was a strip along the coast, 200 km. in length and 20 to 25 km. broad. The direction of the shocks came from the sea, and the epicenter is sup-

¹⁵ H. Pontoppidan, "Verslag over de aardbeving op 26 Juni, 1914, in de residentie Benkoelen." *Jaarb. v. h. Mijngwezen*, 2, 78, 1914.

As to the position of the epicenter van Nouhuys¹⁷ comes to another conclusion, in connection with the fractured submarine cable Padang-Batavia. This cable was fractured at 5° 3' S. L. and 120° 49' E. L., at a distance of 138 km. from the observatory at Batavia and at a distance of 68 km. from the southern end of the epicentral line of Pontopidan. The sheathing of the cable had been somewhat damaged between two points approximately at a distance of 100 and 130 fathoms from the fracture on the Batavia side and was perfectly intact near the fracture, which showed the characteristics of a sudden tension. The damaged part of the cable was pinched, and van Nouhuys supposes that it had sunk in an opened fracture, which afterwards was closed, while he considers the possibility of another position of the epicenter near the cable-fracture.

The Ceram Earth- and Seaquake of 1899.—Another typical earthquake of tectonic origin was that on the island of Ceram on September 30, 1899.¹⁸ Parts of the northwest coast, and particularly the south coast of the island, were damaged by an earthquake water-wave, which was formed by the submergence of sections of the coast, which caused a sudden flood to heights of 1.7 to 9 meters. It is possible that the movements which occurred on the islands were the result of movements at the bottom of the near-lying deep sea-basins, but without doubt the submergence of the coast was the principal cause of the water-waves, because they were of local occurrence. The shock was felt throughout the Moluccas; from southwest Ceram the propagation was particularly strong in an east and west direction, which points to movements along longitudinal fractures, in contradistinction to the Ambon earthquake of 1898, which followed a fault-line, transversal to the longer axis of the island.

Earthquakes on the Batjan Islands in 1902.—The island of Batjan, to the west of Halmaheira in the northern Moluccas, consists of three parts. The northern part is composed of volcanic rocks and young-tertiary sediments, while at some places older rocks, as granite and gabbro, are uncovered by erosion. In the southern part volcanic rocks have also a great extension. Active volcanoes are wanting on the island. The middle part forms a high mountain-range, which consists of crys-

¹⁷ J. W. van Nouhuys, "De breuk in de Padang-Batavia kabel in verband met de aardbeving van 26-27 Juni, 1914, in de Residentie Benkoelen." *Tijdschr. Aardr. Gen.*, 34, 103, 1917.

¹⁸ R. D. M. Verbeek, "Kort verslag over de aard- en zeebeving op Ceram, den 30 September, 1899." *Natuurk. Tijdschr. v. Ned. Indië*, 60, 219, 1901.

talline schists and intrusive eruptive rocks. In the southern and northern parts upheaved plio-pleistocene deposits are found, while they are entirely lacking in the middle part. This points to the existence of faults which border the higher middle part and hot springs are found at several places in its neighborhood. That other faults and fractures are found on and between the islands of the Batjan group is made probable by the effects of the earthquakes in 1902. On the islands Klein-Tawali and Kasiruta parts of the coast suddenly sank below sea-level and dead trees still emerged from the sea during my visit in 1915. Klein-Tawali was wholly surrounded by a zone with emerging trees and along the whole western coast of Kasiruta parts of the coast had disappeared. In 1902 six persons were killed by a water-wave at Toamada (North Kasiruta) and at Labuha (Batjan) eighty-four earthquakes were felt within three weeks (in one night thirteen), the direction of which was nearly always N-S.

CONCLUSIONS

1. The East Indian archipelago can be divided in a stable western and an unstable eastern part. The western part is unstable in the neighborhood of the Indian Ocean.
2. There is a close relationship between earthquakes and tectonic lines.
3. A coincidence of earthquake zones with zones of active volcanoes sometimes exists, but is often entirely wanting. The movements of the earth's crust between lines of fissure may as well accelerate or prevent the penetration of the crust by the molten magma.
4. The seismotectonic lines are transversal, diagonal or longitudinal fractures, along which displacements in the zone of fracture accompany displacements in the zone of flow.
5. The epicenters of most earthquakes of the last twelve years, of which the epicenters have been calculated, *are under water*.
6. The position of most epicenters on one of the submarine slopes of geanticlines can be explained by important movements of the geanticlinal axis in a horizontal direction.
7. Considerable transverse fracture-movements occur in regions with important differences in velocity for neighboring points of the horizontal projection of the geanticlinal axis—for instance, near the bending-points of this projection of the axis.
8. Earthquakes along transverse tectonic lines and older folds cut off by the present coast-lines may often be found in the same region, because they *both can be surface expressions of differences in the rate of horizontal movement* between adjacent parts of the geanticline.

DELFT, HOLLAND, June, 1921.

A SEISMOGRAPH CONSTRUCTED ON A NEW PRINCIPLE ¹

By H. MORIZE

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The fundamental problem of seismology consists in the determination, at a given moment, of the acceleration of a given point on the earth's surface that has been set in motion by an earthquake at some distance. For this purpose use is made of seismographs which are instruments made of heavy masses so arranged as not to be affected by the movement of the ground itself, and which, for this reason, will appear, on account of the relative motion, to be displaced in relation to objects fastened to the earth itself. The relative movement thus obtained is variously registered upon a sheet of paper that moves at a uniform rate, and thus produces the seismogram from which the desired acceleration may be deduced.

As it is not possible to devise an inert mass completely isolated from the earth, observers must manage to get along with a simple approximation to the theoretic principle. As a rule a mass is employed that is heavy enough to revolve about an axis forming a small angle with the verticle. If we call this angle α , and the local intensity of gravity g , the system forms a pendulum capable of oscillating in the following time:

$$t = 2\pi \sqrt{\frac{1}{g \sin \alpha}}$$

When $\alpha = 0$, the period t becomes infinite, and the mass behaves as if it were entirely suspended in space, for as it does not participate in the movements of the ground, it is inert. But it is necessary that when disturbed by a seismic shock, it should return to a definite position of equilibrium and also that, when it reaches this position, it should remain at rest and be ready to receive the next shock that occurs. These are conflicting conditions, for in order to fulfill the first, it is necessary that the angle α , which determines the position of equilibrium, should not be null, for that is the one in which the center of gravity of the mass is in the

¹Translated from Portuguese by Dr. J. C. Branner. We are informed by Mr. H. O. Wood that the principle here described was used by Rev. Father Odenbach, of Cleveland, Ohio, in the construction of a seismograph, which, however, seems not now to be in use.—*Editor*.

vertical plane in which the axis of rotation lies, which evidently requires that it should not be confused with the vertical axis itself. But from these conditions it results that the pendulum has a certain directing force that causes it to oscillate about the position of equilibrium, until its force is absorbed by inevitable friction and by the resistance of the atmosphere.

It is easy to see that this persistence of the oscillation of the mass has a detrimental influence, for if a seismic shock should strike the pendulum while in motion, it would produce very different effects according to whether it were struck while moving in one direction or another, and if the period of the pendulum were the same as the seismic oscillations, the latter would be recorded with an exaggerated amplitude. Furthermore, when the disturbance has ceased, the pendulum continues to vibrate, and will register its own movements, which are to be attributed to the ground, even after the ground has come to rest.

It is therefore necessary that the pendulum should have a well-determined position of equilibrium, and at the same time that its period should be determined, which can be done imperfectly by having the angle α very small, and by using dampers to absorb the oscillations of the pendulum itself. The best method thus far discovered for this damping is that invented by the eminent Russian seismologist, the late Prince B. Galitzen, who proposed to swing the pendulum between the poles of a powerful magnet. By induction a current is produced in an electrical circuit connected with the moveable pendulum, and this passes through a galvanometer where it is absorbed in the form of heat, while it causes the movable apparatus and the mirror to move at angles corresponding in amount and direction to the movement of the mass of the pendulum. These movements of the galvanometer are registered by the Poggendorf method by a ray of light falling on a moveable drum covered with photographic paper, so that the seismic curve is thus registered without friction, and sufficiently damped to eliminate the parasitic waves produced by the pendulum itself.

It has occurred to me to use a very different method of arriving at the same result, and at the same time to do away with the movements of the pendulum and with the dampers, which are always difficult to regulate, and which considerably reduce the sensitiveness of the apparatus.

The electric resistance of granulated carbon is considerably reduced by an increase of pressure, and this property has long been made use of in microphones in the ready transmission of the minor and rapid changes of pressure caused by a diaphragm vibrating under the influence of the

complicated sound waves produced by the human voice. The fact that these rapid changes are correctly reproduced shows that that material has a marked and spontaneous aperiodicity, for if once set in motion by the first wave, it would continue to vibrate, the subsequent and different waves which produce articulate sounds would be interfered with by the earlier vibrations, and it would be impossible to reproduce the voice.

Let us see how these principles can be applied to the seismograph.

Suppose we have a mass M so suspended as to be aperiodic by means of a bifilar system between two rigid pieces A and B (Fig. 1), which

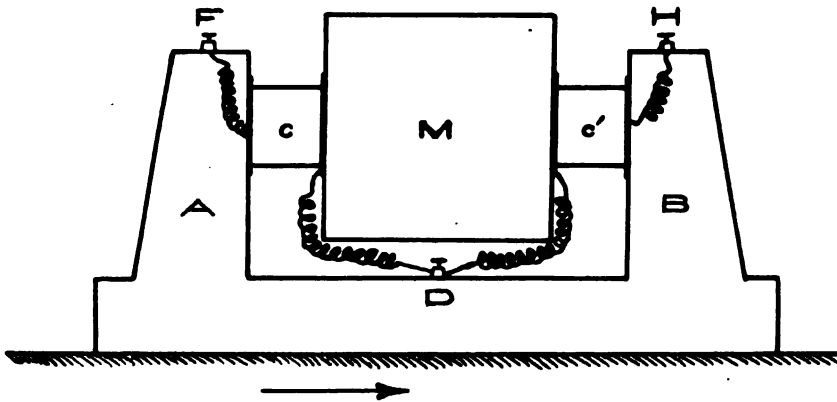


Fig. 1.

are securely fastened to the earth and which partake of the earth's movements. In the spaces between the mass M and the fixed pieces are two blocks c and c' made of granulated carbon, and contained in coverings of an electrically insulating substance that maintains their external shapes. By the interposition of c and c' the mass M occupies a position of equilibrium, about which it can have vibrations of only infinitesimal amplitude.

If there comes through the earth and from the direction indicated by the arrow a seismic disturbance with an acceleration of j , the pieces A and B will exert a pressure upon the mass M which will tend to increase on the side c and to diminish on the side c' , the existing pressure which we shall call P . On account of the reaction of the mass M these vibrations will be $r = Mj$ on the carbon c , and $r = -Mj$ on c' , while the total respective pressures will make $p = F + Mj$, and $p' = F - Mj$.

The electric resistance of c and c' are functions of the pressures, to which, as a first approximation, we may admit that they are inversely proportional. If R were the electric resistance of the carbon c in a state of repose, and R' the resistance, under the same conditions, of c' , we should have the following expressions (in which K is a coefficient of proportionality) when a seismic wave having an acceleration of j reaches the apparatus.

$$\text{(On the side of } c) \quad R = \frac{K}{F} \quad (1)$$

$$\text{(and on the side of } c') \quad R' = \frac{K}{F'} \quad (2)$$

in which F and F' are the respective forces with which the same central M is compressed by the two carbons.

Whenever this mass tends to move, these expressions become:

$$R - r = \frac{K}{F + Mj} \quad (3)$$

and

$$R' + r' = \frac{K}{F' - Mj} \quad (4)$$

in which r and r' are the variations of the resistances R and R' caused by the variation of the force Mj , which is positive on one side and negative on the other.

When resolved in relation to K we have:

$$(R - r)(F + Mj) = K \quad (5)$$

and

$$(R' + r')(F' - Mj) = K \quad (6)$$

from which we have finally:

$$j = \frac{F'R' - FR + F'r' + Fr}{M(R - R' + r' - r)} \quad (7)$$

which equation will give j , in terms of the constants F , F' , R , R' and of the variations of resistance of the carbons r and r' .

Formula 7 is much simplified if we admit that the initial resistances R and R' are equal, which is easily done, and that the forces F and F'

by which the mass M is pressed by the carbons, are also identical. We then have:

$$j = \frac{Fr}{RM} \quad (8)$$

which allows us to establish the most effective conditions of sensitivity, that is, the greatest value of r , the independent variable, for the given value of j :

$$r = \frac{RM}{F} j \quad (9)$$

A simple inspection of this formula shows that the apparatus will be sensitive in proportion to the size of the mass M and to the initial resistances R of the carbons, and that the initial force that compresses them will be as small as possible, without its going below a certain value, but being subject to negative variations, there may be interruption of the contact between the different pieces.

Let us now see how we can measure successively the variations of resistance at any moment, in the circuit on which depends the value of the acceleration sought. (Fig. 2.)

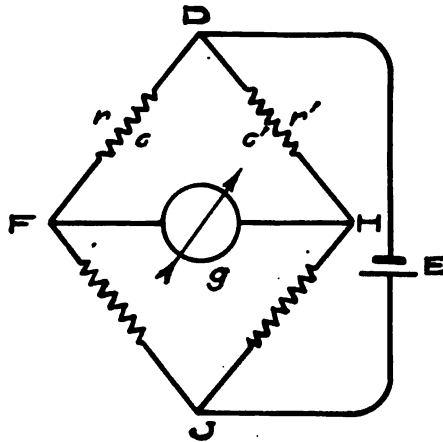


Fig. 2.

If we form a Wheatstone bridge with the resistances R of the carbons and two other variables M , that we can so adjust that they are equal, no current will pass through the diagonal of the galvanometer.

But as soon as there is an earthquake and the resistance turns from the side $R + r$, and from the other, $R - r$, the galvanometer will be crossed by a current having an intensity and direction that varies with the difference $2r$ of the resistance of the carbons whose intensity will be expressed by the following equation:

$$i = \frac{2 m r E}{[2Rm + g(R + m)][2b + R + m]} \quad (10)^2$$

in which E = electric motive force of the battery

g = resistance of the galvanometer

b = the internal resistance of the battery

m = the adjustable resistance of the two arms of the bridge.

It is seen that in order to determine the value of r one can use whatever intensity he chooses by selecting the values E , g , b and M to suit his convenience. Thus in place of a photographic register, which is always inconvenient and expensive, it will be possible to use a mechanical register with pen and ink on the rotating drum of a registering galvanometer.

² This is the formula of S. P. Langley published in the *Proceedings of the American Academy of Arts and Sciences*, 16, January, 1881: "The Bolometer and Radiant Energy," and devised for the use of the bolometer, which is identical in principle with the type of bridge adopted, with the original letters replaced by those corresponding to the present case.

THE CHITTENDEN EARTHQUAKE OF JULY 24, 1921

By WILLIAM KEMNITZER

On the evening of July 24, 1921, a moderately severe earthquake was felt throughout several counties of central California. The shock was slight in Santa Clara and Santa Cruz Counties, although it was distinctly felt in San Francisco, San Mateo, Monterey, and San Benito Counties. The seismograph record from Santa Clara University recorded the time as 9:04:30 p. m., and the time from the Mt. Hamilton seismograph was at 9:04:56. In all, the tremors which could be perceived without instruments were felt over an area of approximately 3,200 square miles.

Although the earthquake was not severe enough to do any material damage even in the zone of highest intensity, it was considered by many in this region to be the most severe shock since the earthquake of April 18, 1906.

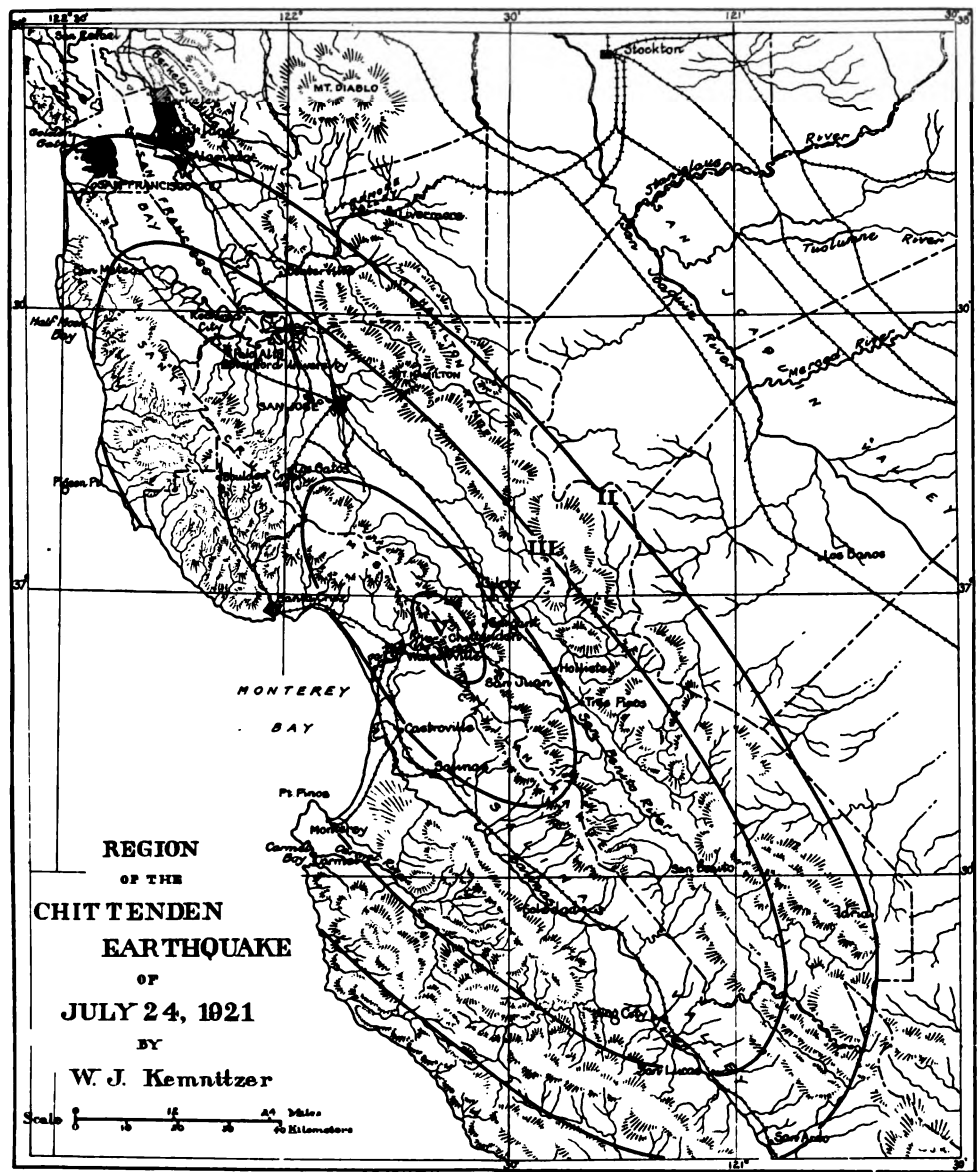
After an investigation in the field the epicenter was definitely located near the town of Chittenden in Santa Cruz County. Not only was the shock most severe at this point, but with remarkable consistency the isoseismals of lesser intensity have their centers at this point. Since no recent surficial evidence could be observed in the field, the first movement must have been of a subterranean nature. The intensity of the shock at the epicenter, although quite high, can not be classed as over V in the Rossi-Forel scale. At this point, which is on firm rock, the shock was generally felt by everyone; persons asleep were awakened; movable objects were overturned; and milk was thrown from open pans. Practically every person in the region of highest intensity said the tremors were preceded by a distinct rumbling sound, somewhat like that of a fast-moving train.

More or less equidistant from the epicenter are the towns of Gilroy, Watsonville, Salinas, and Hollister. These towns are built upon alluvium, and, without exception, the intensity of the shock in these places was somewhat higher than at places at equal distances from the epicenter that were on solid rock. This was always the case in the mountain valleys, where the people living in the valley would describe the shock as having a higher intensity than those who were on the mountain within a few miles from them.

The San Andreas fault, which was the center of disturbance for the earthquake of April 18, 1906, runs close to the epicenter of this recent earthquake and takes a NW.-SE. direction from this point. The isoseismals of this recent disturbance form almost perfect ellipses about the epicenter, the major axes being identified with the San Andreas rift. From the elliptical shape of the isoseismals it is obvious that the disturbance took place along a line running in a NW.-SE. direction, but there is no definite reason for supposing that the disturbance took place along the known San Andreas fault. Geologically the region of highest intensity is one of many contacts and faults, and the disturbance may have taken place along any of the many faults that are so close to the epicenter. With remarkable consistency the tremors that were perceptible to human beings died out about eighty miles northwest of the epicenter and at the same distance southeast of it. Along the minor axes of the ellipses formed by the isoseismals the tremors died out with equal consistency.

Calculations from the records of the seismographs checked the location of the epicenter against the field work. The calculated epicenter was 25.4 miles from Mt. Hamilton, and 71.9 miles from Berkeley.

Circles drawn about these points with the respective radii intersect close to the town of Chittenden, in Santa Cruz County.



THE EAGLE LAKE EARTHQUAKE OF JULY 21, 1921

By WILLIAM KEMNITZER

During the week from July 18 to 24, 1921, the region about Eagle Lake, Lassen County, California, experienced several slight earthquake shocks. The first shock noted was on Monday, July 18th, about 8:15 a. m., followed by another at 12:15 on the same day. On Wednesday morning, July 20th, a third shock occurred between six and seven o'clock, and on Thursday, at 12:35 p. m., the most severe one of all was experienced.

The region about Eagle Lake is very sparsely settled, and it was with difficulty that data concerning intensity were collected in the field. Nearly all of the persons questioned said that slight tremors were of a common occurrence. It was interesting to note that every one connected these tremors with the action of Lassen Peak, which is distant about thirty-eight miles in a direct line. As a matter of fact the shocks were not felt at Lassen Peak, but had their origin some forty miles to the west.

The most important shock, that of Thursday, July 21st, was recorded on the seismograph at the University of California in Berkeley as having taken place at 12:18 p. m., Pacific standard time. Within five minutes, with intervals of about two minutes, three shocks were felt in the Eagle Lake district. The second was the most severe and the one recorded on the seismograph.

Along a route nearly on a direct line from Berkeley to Susanville, the first place where the shock was felt was at Crescent Mills. From this place, the intensity increased toward Susanville. At Susanville the intensity data were gathered from outlying places by direct inquiry over telephone.

The Lassen Weekly Mail of Susanville published the following article at the time of the earthquake:

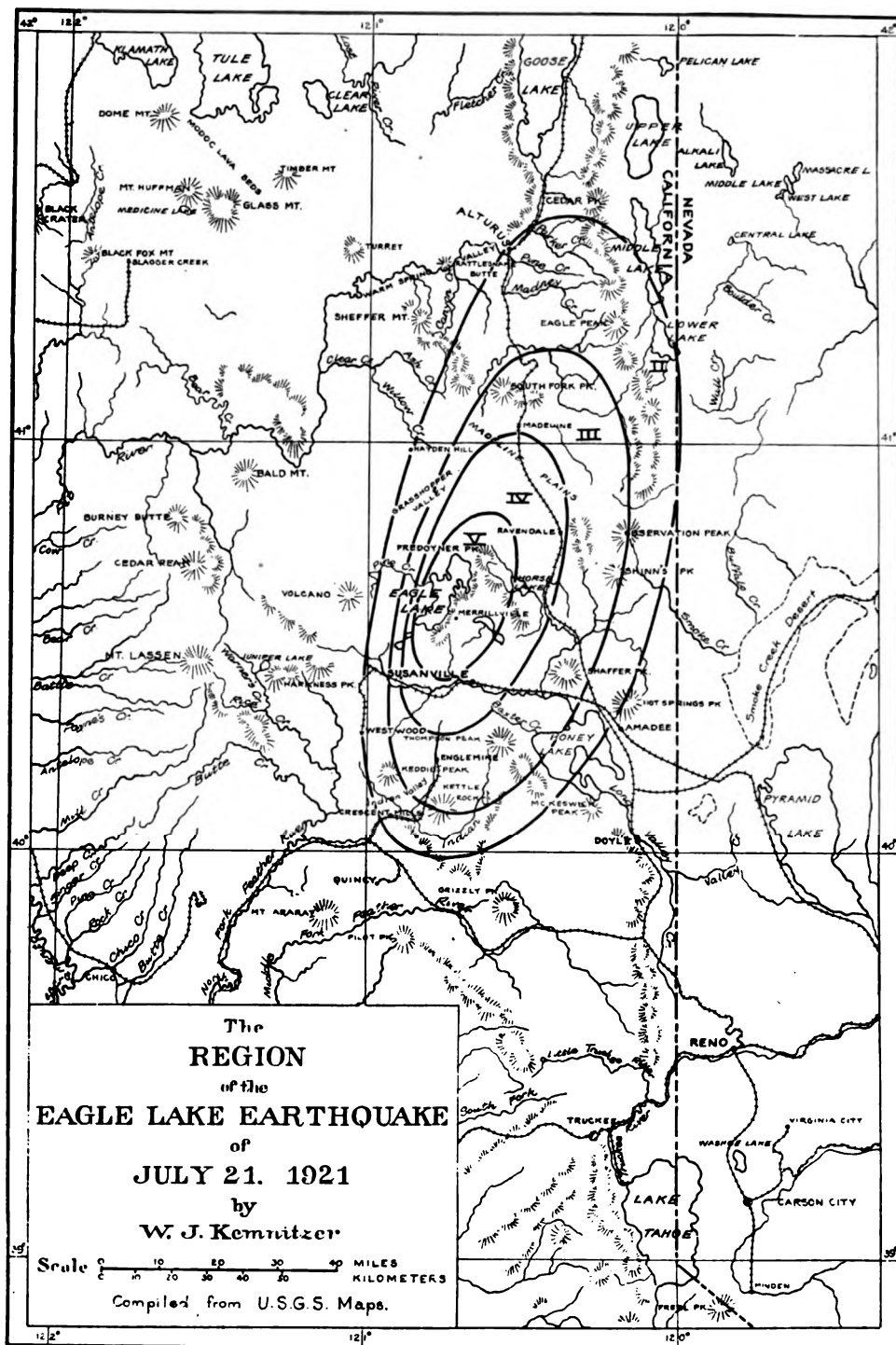
A fire alarm was turned in from the Del Mar building about one o'clock Thursday. The blaze was extinguished without it doing any damage. An investigation disclosed the fact that the earthquake shock that day had disconnected the oil pipes which supply the oil burner in the basement. Several bricks in the chimney were displaced and this forced the burning oil into the firebox in such a way that the smoke filled the room. This was what occasioned the fire alarm.

This account would place the intensity as V at Susanville, but since the

general intensity in Susanville and its vicinity was not so severe, little credit was given this report.

The region in the immediate vicinity of Eagle Lake received the most severe shock. At several ranch houses on the east shore of the Lake objects were knocked over and several persons had difficulty in keeping their feet. On the west shore the shock was not so intense, and it died out very rapidly in this direction. The topography about the Lake shows a number of fault scarps, the Lake itself evidently having been formed by gigantic faulting. Due to the ellipse formed by the isoseismals, whose major axis extends in a NE.-SW. direction, the located fault plane extends along the east shore of Eagle Lake. There is no doubt that a subterranean movement occurred along the fault plane on its east shore. Computations from the seismographic records at Berkeley located the epicenter of these shocks at the middle of Eagle Lake.

The whole of eastern Nevada and that part of California in which Eagle Lake lies is made up of mountain ranges that have been formed by faulting. Many recent fault scarps can be seen in the vicinity of Susanville, where slight earth tremors are of common occurrence.



EARTH DISTURBANCES AT DIXIE, WASHINGTON,
SEPTEMBER 14, 1921

By GEORGE EBY.

Dixie, a little village of perhaps one hundred and fifty people, is situated at the forks of a "U"-shaped valley about one-half mile wide, through which a small stream runs. The elevation of the place is approximately 1,500 feet. The village is five miles from the foot of the Blue Mountains.

At the mouth of one of the forks is a large rock quarry which has been operated for about eight years and, as a result, one quite large cliff has been practically removed. The quarry is composed of basaltic rock with considerable sedimentary calcium-carbonate in the crevices.

No earth disturbances previous to September 14, 1921, had ever been recorded. On the night of the 14th I was sleeping in an open building, with the bed placed directly on the ground. The first disturbance came at approximately three o'clock in the morning. It was quite severe, but, since it was just a solitary jar, it could not arouse one sufficiently from sleep in time to make careful observations.

Everything was then quiet until five o'clock, when there was a very sudden blow, accompanied by a sound like that of a deep blast of dynamite in rock. This sound was instantaneous with the jar and of sufficient volume to be heard easily and distinctly, but not great enough to justify the severity of the shock. That is, I have observed that a blast at the quarry with perhaps one-fourth the disturbing force would have a report with about ten times the intensity, and coming considerably after the jar.

The shaking of the ground was not a continued vibrating or rocking motion, but was just one sudden blow. The action seemed to be vertical rather than horizontal. The bed was shaken quite perceptibly and the building was also visibly shaken and agitated enough to rattle a great deal. An automobile, which was standing within three feet of the bed, was observed to have no horizontal or rocking motion. The movement was comparable to that caused by a car on hitting a sharp bump.

About a minute later, there were three tremors following each other in close succession. The sound and motion of each succeeding one was exactly the same as the first, except weaker. Within the next ten

minutes there were four other independent shocks, similar, but growing rapidly weaker. Then five minutes later there were several light decreasing tremors, each accompanied by a sound correspondingly less audible. These diminished until they could no longer be detected.

But the surprising thing to me about all the jars was that I could distinguish no difference in time between the shock and its sound. This even held true with the minor trembling. These last reports resembled in tone and volume a blast at a great distance.

No damage in the nature of broken chimneys was observed, although some smaller articles were disturbed.

These shocks were not noticed by the farmers who lived more than a mile away from town, although some people in Waitsburg, ten miles distant, and College Place, fifteen miles, claimed to have felt them slightly.

Careful inquiry brought forth no evidence that any large explosions had been set off in the vicinity, or that any of the dynamite in the quarry had been disturbed.

WHITMAN COLLEGE, WALLA WALLA, WASH.

SEISMOLOGICAL NOTES

Virginia, July 15, 1921.—A report from Norfolk, Va., states that heavy seismic disturbances were felt in Virginia and parts of West Virginia and Tennessee on July 15, 1921. The hour is not stated. In the district around Mendota, Virginia, considerable damage resulted from the breaking of windows, twisting of frame buildings, etc.

Stanford University, California, July 24, 1921.—A light single shock sufficient to make houses creak was felt at Stanford University on July 24, 1921, at 9:05 p. m. (Pacific Standard time). One person reported that a sound like that of wind preceded the shock. This is the shock which had its epicenter near Chittenden, Santa Cruz County, an account of which may be found in this number of the BULLETIN.

Leghorn, Italy, August 1, 1921.—A dispatch to the *London Times* reports the occurrence of a violent earthquake at Leghorn, Italy, and vicinity on August 1, 1921. Heavy damage was reported in the Lake Lugano district, and a large building is said to have collapsed at Bari, burying many persons.

New Canton, Virginia, August 7, 1921.—A dispatch from New Canton, Virginia, published in the *Richmond Times-Dispatch* of August 10, 1921, states that a severe earthquake shock was felt in New Canton and surrounding towns on Sunday morning, August 7th, at 1:30 o'clock. Many persons were awakened by the rattling of dishes, furniture, and windows. Professor Stephen Taber writes that the shock probably originated in the slate belt of Buckingham County and that its intensity was probably about V on the R.-F. scale.

A later article published in the *Richmond Times-Dispatch* for August 15th states that the authorities of the McCormick Observatory of the University of Virginia believe that the disturbance was caused by the bursting of a meteor rather than by an earthquake. Some evidence is given to support this belief.

San Diego, California, September 8, 1921.—A slight earthquake was felt at San Diego shortly before 11:30 a. m. on September 8, 1921.

Dixie, Washington, September 14, 1921.—Earthquake shocks were felt at Dixie, Washington, in the early morning of September 14, 1921. A short account of these disturbances, by Mr. George Eby, may be found in this number of the BULLETIN. These shocks were not recorded on the seismograph at the Gonzaga University, Spokane, Washington.

Portland, Oregon, September 22, 1921.—A slight earthquake was felt by many persons at Portland, Oregon, at 11:20 a. m. on September 22, 1921. It is said to have continued for twenty seconds, but was not of sufficient intensity to do any damage.

Southern California, September 26, 1921.—Reports from Ontario, San Bernardino and Riverside in Southern California state that a slight earthquake was felt in these places at 2:45 p. m. on September 26, 1921.

Los Angeles, California, September 29, 1921.—Several light shocks were felt in Los Angeles and vicinity, and as far as Riverside, seventy miles distant, at about 9 a. m. on September 29, 1921. The tremors were of very short duration, and no damage resulted.

Elsinore, Utah, September 29, 1921.—Elsinore, Utah, and several near-by places were severely shaken by earthquake shocks on September 29, 1921, and several subsequent dates. A full account of these disturbances by Professor Frederick J. Pack, of the University of Utah, may be found in this number of the BULLETIN.

Harrisburg, Illinois, October 1, 1921.—Two distinct shocks, believed to have been earthquakes, were reported as having been felt at Harrisburg, Illinois, at 3 a. m. on October 1, 1921. They were of sufficient intensity to arouse persons asleep, but no damage was reported.

Pacific Ocean, October 15, 1921.—The seismograph of the United States Weather Bureau at Chicago, Illinois, recorded tremors from a distant earthquake on October 15, 1921. The disturbances on the seismograph began at 12:27 a. m. and lasted for two and one-half hours. The records indicated that the center of the disturbance was nearly 3,000 miles to the southwest of Chicago, probably in the Pacific Ocean.

Balboa, Panama, October 17, 1921.—An earthquake shock lasting

four minutes (?) was felt throughout the Isthmus of Panama on October 17, 1921. The canal was not damaged.

Mexico City, Mexico, November 1, 1921.—Newspaper dispatches report that the Mexican capital was visited by a severe shock at 9 p. m. on November 1, 1921. There was no material damage, but the director of the Mexican Opera Company is reported to have dropped dead from fright. Several other shocks are reported to have occurred in the two days following November 1st.

Lima, Peru, November 2, 1921.—An Associated Press dispatch stated that four sharp earthquake shocks were felt in Lima, Peru, on the morning of November 2, 1921. The center of the disturbance was thought to be near Inca, about two hundred miles southeast of Lima. The inhabitants of Inca were greatly alarmed and took refuge in the city parks.

Bakersfield, California, November 15, 1921.—Two slight earthquake tremors were felt at Bakersfield, California, at 6:25 a. m. on November 15, 1921.

Kingston, Jamaica, November 25, 1921.—Mr. J. T. Brennan has kindly sent a record of a sharp earthquake shock which was felt at Kingston, Jamaica, on November 25, 1921, at 1:17 p. m. (75th meridian time). The shock lasted about twelve seconds, and according to the seismometer of the United States Weather Bureau Office the extreme horizontal movement was about one-tenth of an inch. The shock was felt over nearly all of the island, and the greatest intensity seemed to be on a line joining Kingston and Buff Bay.

El Centro, California, December 4, 1921.—Mr. J. Miles Bartley reports that two shocks were felt at El Centro, California, on December 4, 1921, the one at 11:40 a. m. and the other at 1:40 p. m. Pacific standard time.

Italy, December 9, 1921.—An Associated Press dispatch from Rome stated that serious earthquake shocks had been felt in the region around Lake Bolsena, about sixty miles northwest of Rome, for several days preceding December 9th. The dispatch states that large fissures were

opened in the ground at various places, and that most of the inhabitants were camping in the fields after the earthquakes.

Tokyo, Japan, December 9, 1921.—Reports from Tokyo under date of December 9, 1921, state that numbers of persons were injured and many houses were damaged by the worst earthquake that had been felt in Tokyo in twenty years. The water supply of the city was said to have been cut off.

Rockwood, Tennessee, December 15, 1921.—An earthquake of considerable intensity was felt at Rockwood and various parts of Tennessee at 8:45 a. m. on December 15, 1921. Near Kingston the shock was of sufficient intensity to shake pans and tableware from cupboards.

Guam, December 17, 1921.—A severe earthquake was felt at Guam at noon on December 17, 1921. No damage was done.

Lima, Peru, December 18, 1921.—An Associated Press dispatch from Lima, Peru, under date of December 18, 1921, reads as follows: "The seismographs of the Lima Geographical Society at 10:30 a. m. to-day (Sunday) registered a violent earthquake at a point estimated to be about 530 kilometers from Lima, possibly in Cajamaroa, a northern department of Peru. The agitation lasted forty-five minutes."

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ROSSI-FOREL SCALE OF EARTHQUAKE INTENSITIES

- I. **Microseismic shock:** recorded by a single seismograph or by seismographs of the same model, but not by several seismographs of different kinds; the shock felt by an experienced observer.
- II. **Extremely feeble shock:** recorded by several seismographs of different kinds; felt by a small number of persons at rest.
- III. **Very feeble shock:** felt by several persons at rest; strong enough for the direction or duration to be appreciable.
- IV. **Feeble shock:** felt by persons in motion; disturbances of movable objects, doors, windows; creaking of ceilings.
- V. **Shock of moderate intensity:** felt generally by everyone; disturbance of furniture, beds, etc., ringing of swinging bells.
- VI. **Fairly strong shock:** general awakening of those asleep; general ringing of house bells; oscillation of chandeliers; stopping of pendulum clocks; visible agitation of trees and shrubs; some startled persons leave their dwellings.
- VII. **Strong shock:** overthrow of movable objects; fall of plaster; ringing of church bells; general panic, without damage to buildings.
- VIII. **Very strong shock:** fall of chimneys, cracks in walls of buildings.
- IX. **Extremely strong shock:** partial or total destruction of some buildings.
- X. **Shock of extreme intensity:** great disaster, buildings ruined, disturbance of the strata, fissures in the ground, rock-falls from mountains.

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